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Sub-Surface Structural Analysis of the Appalachian Basin in Morrow County, Ohio

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SUB-SURFACE STRUCTURAL ANALYSIS OF THE APPALACHIAN BASIN IN MORROW COUNTY, OHIO

By

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1 ABSTRACT

Located in the western most region of the Appalachian Basin, Morrow County, Ohio, was once one of the largest oil-producing regions in the nation and continually produces today. To date, approximately 30 million barrels of oil and 6.5 billion cubic feet of gas have been produced, primarily from the Copper Ridge Dolomite. Past studies suggest that regional remnant doming within the Copper Ridge accounts for production, however it is hypothesized that faulting within the basement rock exerts an important control on trapping and migration of hydrocarbons. In order to gain insight into the underlying structure and the causes of significant hydrocarbon production in Morrow County, this study characterized structural architecture of the basement in the region by analyzing well log data from 2,662 wells to create structure, isopach, trend surface, and residual maps. A key objective of this study was to correlate stratigraphic horizons across the county within Cambrian-Ordovician strata to determine locations of thinning and thickening that are translated throughout the strata, disruptions to the structure maps indicating potential faults (i.e., lineaments), and correlate those lineaments to the four consecutive orogenies spanning from Early Cambrian through Permian time in the Appalachian Basin.

Nine lineaments trending in a northwest-southeast orientation and five lineaments trending in a northeast-southwest orientation resulted from this study (14 in total). These lineaments were located by tracing the outlines of highs or lows in the residual maps, and

verified and interpreted by observing the isopach maps and lithofacies. The deformation associated with the lineaments trending in both orientations represent extensional horst-graben sequences; the northwest-southeast trending lineaments in the northwestern portion of the county, and the northeast-southwest trending lineaments in the southeastern half of the county.

The northwest-southeast lineaments likely originated in relation to Precambrian midcontinent rifting and reactivated during the four subsequent Paleozoic orogenies (Taconic, Salinic, Acadian and, Alleghanian). The second set of lineaments trending northeast-southwest can be linked to the creation of the Rome Trough (Early to Middle Cambrian) and were likely reactivated during the four Paleozoic orogenies. Both sets of lineaments appear to have been reactivated during deposition of these Cambrian-Ordovician strata, creating localized thinning and thickening adjacent to the discerned lineaments. Furthermore, these lineaments appear to have undergone additional reactivation since deposition of these strata, as they act as a migration pathway allowing for migration of hydrocarbons into the remnant domes within the Copper Ridge Dolomite (Knox Group) and leakage from these reservoirs as well.

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4 INTRODUCTION

Throughout the 1960s, Morrow County, Ohio, was one of the largest oil-producing regions in the nation and continues to produce today, with approximately 30 million barrels of oil and 6.5 billion cubic feet of gas produced from Morrow County since 1959 (McClish and Roberts, 1989; DrillingInfo, 2020). Following the boom of the 1960s, insufficient exploration within the region resulted in an unclear explanation for a large amount of oil produced from this part of the Western Appalachian Basin (Figure 1). The Copper Ridge Dolomite is the primary producer in the area and the hydrocarbons source from an unknown unit that may be locally absent but occurs extensively down dip (Dolly and Busch, 1972). Additionally, it is speculated that faulting within the basement rock and regional remnant doming exerts an important control on trapping, and may explain the high volume of oil produced from Morrow County (Blaxton, 1996).

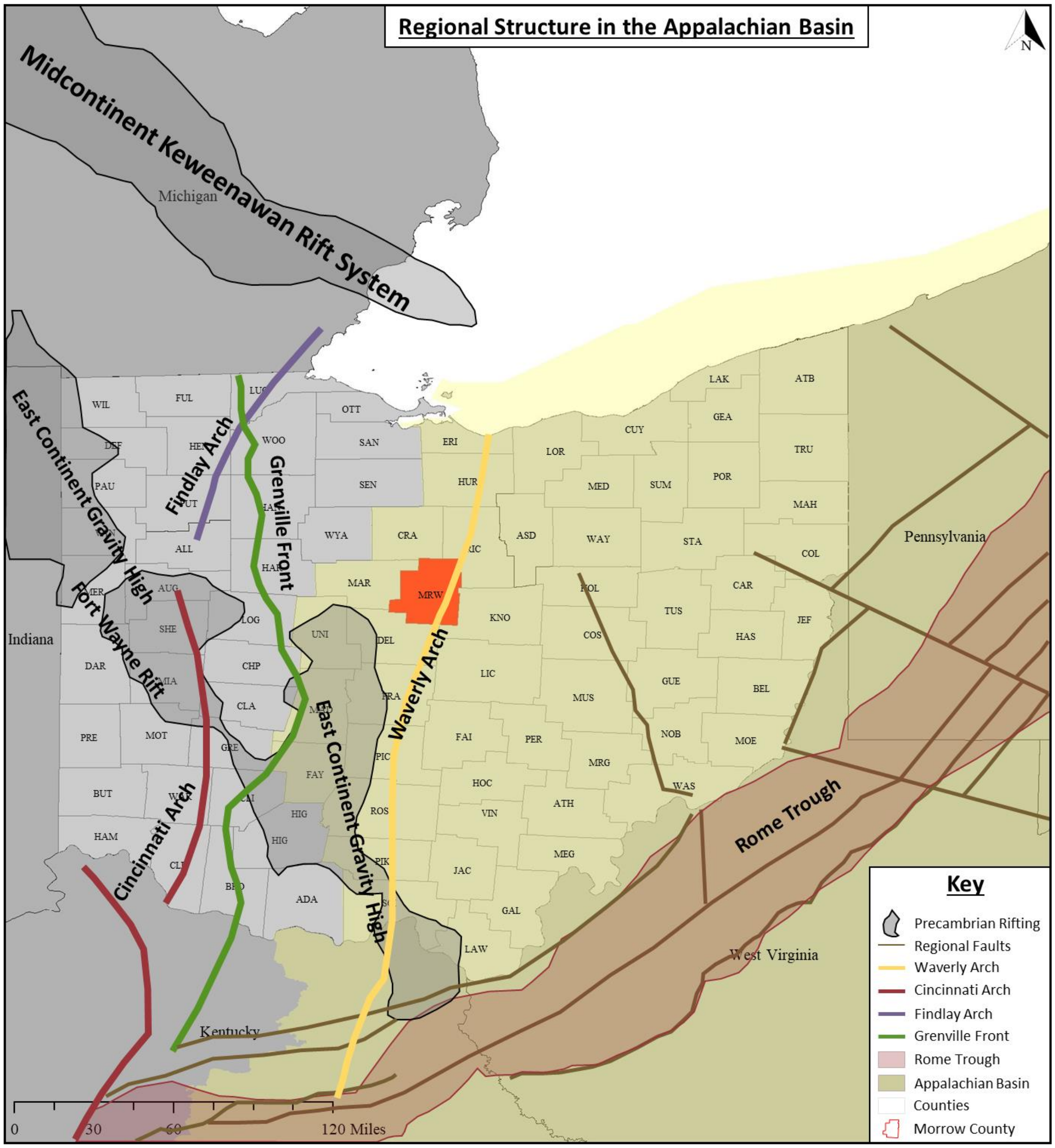

Figure 1. Regional structure of the Appalachian Basin, United States. Morrow County is outlined in red (Modified from: East Continent Gravity High/Fort Wayne Rift/Midcontinent Keweenawan Rift System: Drahovzal et al., 1992; Grenville Front/ Cincinnati, Waverly, Findlay Arch/Rome Trough/Regional Faults: Popova, 2017).

The structural architecture of the Appalachian Basin was controlled by four consecutive orogenies spanning from Early Cambrian through Permian time, with each subsequent orogeny imposing collisional tectonics in a general northeast-southwest orientation (Ettensohn, 2008). Prior to these orogenies, this area had undergone multiple intracratonic rifting stages (i.e., Midcontinent Keweenawan Rift (1.0-1.2 Ga)), the uplift of the Grenville Orogeny, and the rifting stage following the Grenville orogenic event (i.e., Rodinian fragmentation). These tectonic events are responsible for known structural features found throughout Ohio and the Appalachian Basin. Precambrian faulting is hypothesized to be responsible for the fabric of most lineaments throughout Ohio and the Appalachian Basin, with reactivation occurring during the four subsequent Paleozoic orogenies.

Although far-field tectonics within the Appalachian Basin have been widely noted (Gordon and Hempton, 1986; Ettensohn, 2008), geologic publications pertaining to faulting in the Morrow County area are sparse. Shearrow and Preston (1965) discussed the impact that the Waverly Arch had on Morrow County structure, and the structural influences hydrocarbon migration from down dip. Isopach maps were created on basement to the top of the Trenton Limestone (Late Ordovician), and these maps revealed that the Waverly Arch formed from Late Cambrian through Early Ordovician time and trended north-south (Shearrow and Preston, 1965). The north-south trend of the arch provided a migration pathway for hydrocarbons to migrate from down dip and be trapped into the erosional remnants within the Copper Ridge Dolomite.

Dolly and Busch (1972) discussed the source of the hydrocarbons and how the pre-Ordovician structure played a role in trapping hydrocarbons. Similar to Shearrow and Preston (1965), Dolly and Busch (1972) created isopach maps on the basement-Knox unconformity strata, to understand the timing of the Waverly Arch. They also created structure maps on the lower Chazy Limestone (Wells Creek Formation) and overlaid them onto the Knox unconformity structure map to locate the erosional remnant anticlines that are the acting reservoir within the Copper Ridge Dolomite. Following deposition of the Copper Ridge Dolomite (at the time a limestone), subaerial exposure lead to the erosion of the limestone, leaving remnant anticlines that eventually became the acting reservoirs. As Ordovician deposition occurred, water percolated down into the Copper Ridge strata, mass dolomitization occurred, ultimately creating sufficient porosity and permeability for a complete petroleum system (by Early-Middle Ordovician) (Dolly Busch, 1972).

Shafer (1989) discussed his interpretations on fault patterns within Morrow County based on seismic data. Overall, he found that the structural architect within the county contains normal, strike line faults with transverse dip-slip faults. The approximate average throw on the normal faults are 50 ft (15 m). The compressional tectonism within the Appalachian Basin supports en-echelon strike-line normal faults and horst-graben faulting. Shafer (1989) indicates that the origin of the oil and gas found within the Knox domes is from a deeper source bed, from which upward migration occured through the permeable joints and faults, and he suggested that drilling should focus on stacked targets in the areas of remnant highs and near fault and joint intersections.

In order to gain insight into the underlying structure and the causes of significant hydrocarbon production in Morrow County, this study characterized and mapped the structural architecture of the basement in the region by analyzing well log data from 2,662 wells to create structure, isopach, and trend surface maps. A key objective of this study was to correlate stratigraphic horizons across the county within Cambrian-Ordovician strata to determine locations of thinning and thickening that are translated throughout the strata, and disruptions to the structure maps indicating potential faults (i.e., lineaments). Structural features were then examined for possible hydrocarbon migration and structural trapping by mapping the location, spatial extent, and trend of the remnant doming. Resulting data from this study allows the relationship of these findings to potential exploration within Morrow County, and/or creating an analog for future exploration within similar settings in the Appalachian Basin.

5 GEOLOGIC SETTING

The Appalachian Basin is composed of multistage, retroarc foreland basins that systematically formed due to tectonic loading of four consecutive orogenies on the eastern and southeastern flanks of Laurentia from the Early to Middle Ordovician through the Permian (Ettensohn, 2008). Most of the strata lies on an extensional margin that formed due to the rifting of Laurentia from Rodinia, ultimately forming the Iapetus Ocean (750-535 Ma). During the Early to Middle Ordovician, a foreland basin began to develop due to the tectonic loading from the Taconic Orogeny that created the accommodation space for most of the Appalachian strata. The following three Appalachian orogenies spanned from the Silurian through the Permian: Salinic (Silurian), Acadian/Neoacadian (Devonian-Mississippian) and Alleghanian (Pennsylvanian-Permian).

The Appalachian Basin overlies Grenville crust; that has been dated to 1.35 to 0.95 Ga and is the product of Mesoproterozoic metamorphism (Ettensohn, 2008). The pavement for deposition of the Upper Neoproterozoic-Lower Cambrian strata on top of the Grenville foreland basin was gently sloped, facilitating a near-perfect setting for a rapid transgression of the Sauk Sea. This foreland basin was created through a rift stage lasting approximately 300 my as Laurentia broke apart from Rodinia (Ettensohn, 2008). This break up led to the development of continental embayments along three valleys of rift transform segments (triple junction) (Castle, 2001). As loading increased along the triple junction, subsidence increased in the foreland basins and created three major depocenters (Figure 3A). The structures bounding the three depocenters were reactivated as subsequent orogenic events occurred, controlling sedimentation and structural trends found in each of the depocenters (Ettensohn, 2008).

The Taconic Orogeny began during the Early to Late Ordovician (Figure 3B) and is commonly marked by the Knox Unconformity at the base all throughout the Appalachian Basin. The Knox Unconformity denotes the transition of a passive margin (Grenville) to a convergent margin and the inception of the Appalachian foreland basin (Castle, 2001). The Taconic Orogeny, which consists of three smaller tectophases, started once the eastern margin of Laurentia collided with an offshore arc, forcing the Appalachian continental shelf to uplift and eventually erode (Ettensohn, 2008). The first tectophase consisted of eastward subduction of island arcs along the entire margin; the second consisted of eastern subduction of island arcs along the southern margin; the last tectophase consisted of subduction primarily along the northern margin.

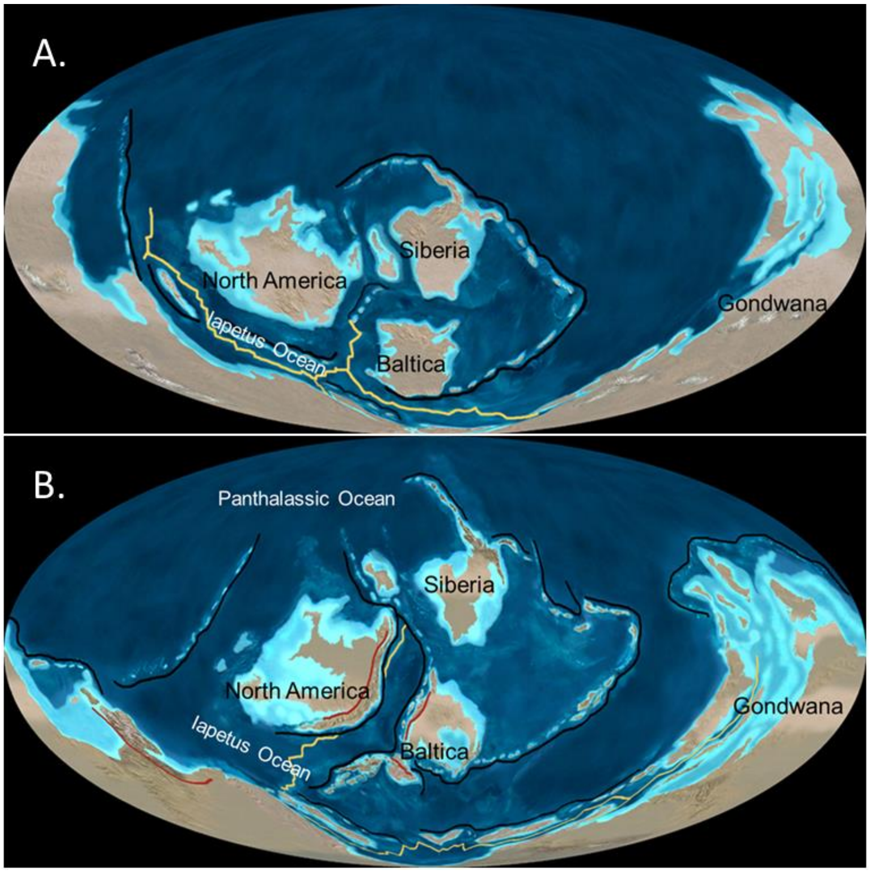

Figure 2. Paleogeographic map spanning the extent of the Cambro-Ordovician strata. A) During the Late Cambrian (500 Ma); Laurentia continued to move north and the Iapetus Ocean continued to open. B) Late Ordovician (450 Ma); subduction on the western margin of B) Late Ordovician (450 Ma); subduction on the western margin of Baltica continued as it approaches Laurentia and the Taconic Orogeny comes to an end (Blakey, 2013).

The Salinic Orogeny occurred throughout the Early to Late Silurian and mostly affected the northern Appalachian Basin, and consists of two southwestwardly migrating tectophases (Ettensohn, 2008). It was the final collision of Baltica with Laurentia, resulting in minor uplift and mass erosion. The end of the Salinic Orogeny (Late Silurian-

Early Devonian) is marked by a brief transitional period of compressional tectonics to extensional block faulting (Ettensohn, 2008).

The Acadian Orogeny began during the Early Devonian and lasted through the Late Mississippian. The Acadian can be broken into four tectophases, with the first consisting of the collision of Laurentia with the Avalonian terrane (Ettensohn, 2008). The basal surface of the first tectophase is indicated by a disconformity marking the base of the Kaskaskian Sloss sequence. The second tectophase occurred during the Middle Devonian and includes the accretion of the New York promontory (Murphy and Keppie, 2005; Ettensohn, 2008). The third tectophase reflects a southward migration of deformation as a collision with the Virginia promontory occurred during the Middle to Late Devonian (Murphy and Keppie, 2005). This is the only tectophase within the Acadian Orogeny to indicate more thrust loading rather than dextral, oblique, strike- slip as seen in the other three tectophases (Murphy and Keppie, 2005). The fourth tectophase (Neo-Acadian) occurred in the Late Devonian to Early Mississippian and is indicated by the magmatism, metamorphism, and deformation in the Massachusetts area created by the accretion of the Carolina and Alabama Terranes (Murphy and Keppie, 2005; Ettensohn, 2008).

The last Appalachian compressional phase was the Alleghanian Orogeny, which spanned from Early Pennsylvanian-Permian time and can be broken into two tectophases. The Alleghanian Orogeny represented the final closure of the Rheic Ocean during the amalgamation of Gondwana and Laurussia, and ultimately lead to the creation of Pangea (Ettensohn, 2008). The majority of the orogeny exhibited oblique convergence; however, in some parts, dextral strike -slip was more common than compressional deformation (fold-thrust belt) (Root and Onasch, 1999; Ettensohn, 2008). The northern Appalachians reflect more complex wrench faulting, but both the southern/central and northern margins are connected via dextral shear zone corresponding to older Precambrian faults (Ettensohn, 2008). During the first tectophase (Early to Middle Pennsylvanian), Gondwana was being subducted below the newly accreted southeastern margin of Laurussia, leading to the development of thrust decollement tectonism (Ettensohn, 2008). In the Late Pennsylvanian to Early Permian, the structural style changes from a fold and thrust decollement tectonism style to a non-decollement, wrench tectonism style, marking the second tectophase (Ettensohn, 2008).

6 STRUCTURAL SETTING AND MAIN STRUCTURAL FEATURES

Structural deformation occurred during each Paleozoic orogeny in the Appalachian Basin, creating new faults and reactivation along preexisting faults. Basement rocks consist of Grenville-aged metamorphic rocks with evidence of normally displaced faults due to extensional tectonics. The most notable faulting system is the northeast-southwest trending faults of the Rome Trough, south of Morrow County. The next fault system is the Bowling Green Fault Zone, located in the northwestern part of Ohio and striking north-south with throw as much as 400 ft (122 m) (Figure 3) (Onasch and Kahle, 1991). Along with the Rome Trough sequence, the Auglaize Fault and Starr Fault systems strike northeast-southwest and are near Morrow County (Figure 3). The remaining faults and lineaments in Ohio tend to strike northwest-southeast, indicating a different tectonic regime most likely from Midcontinent Keweenawan Rifting. The last major structural features found within the region are the Findlay and Cincinnati arches.

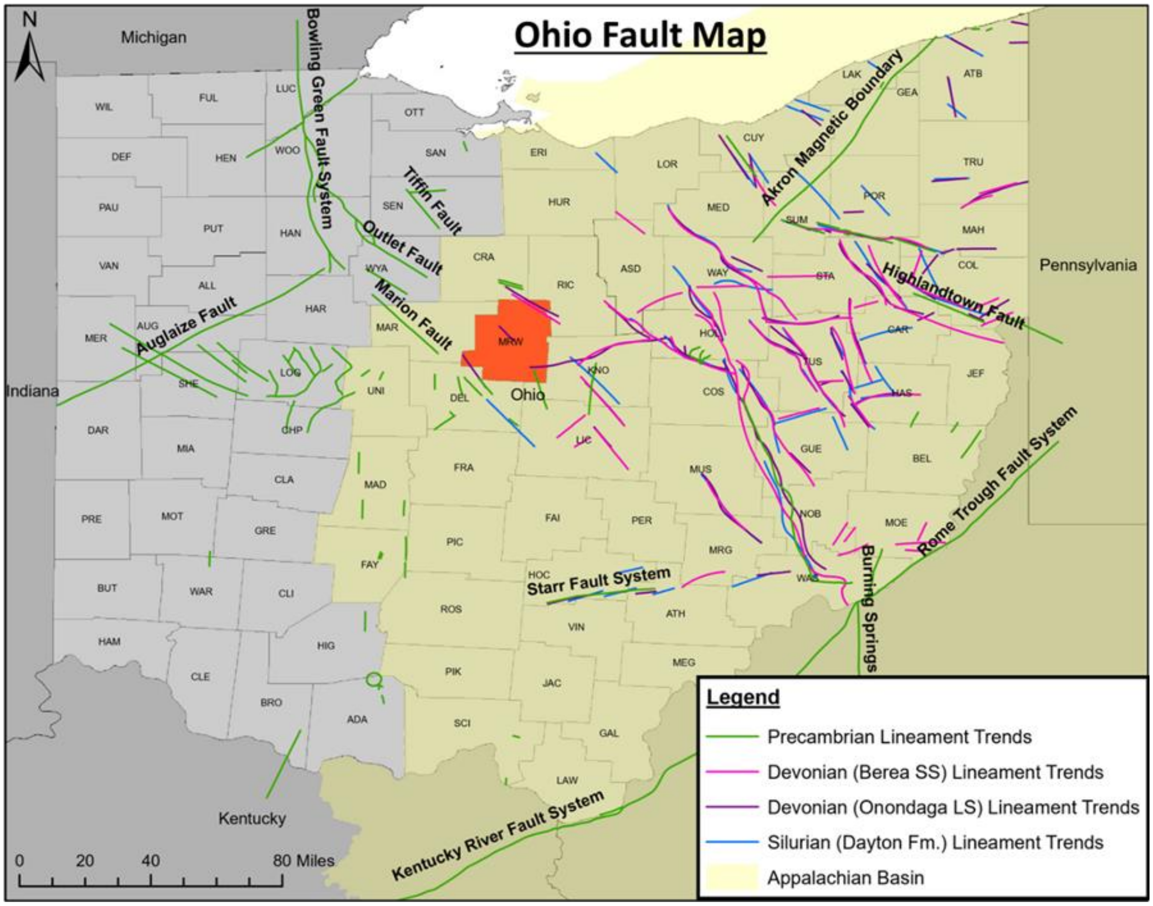

Figure 3. All known lineaments mapped in the state of Ohio. Morrow County is highlighted in red (Precambrian lineament shapefile: Baranoski, 2013; Devonian (Berea SS) lineament shapefile: Solis, 2015; Devonian (Onodaga Limestone) lineament shapefile: Solis, 2015; Silurian (Dayton Fm.) lineament shapefile: Solis, 2015).

The formation of the Rome Trough began during the Early to Middle Cambrian, as rifting began to form the Iapetus-Rheic Ocean (Gao et al., 2000). The Rome Trough is an interior rift system that extends into the Appalachian foreland in eastern Kentucky and western West Virginia where it follows the northeast-southwest trending magnetic gradient known as the New York-Alabama lineament (Gao et al., 2000). The Rome

Trough is divided into three segments: the eastern Kentucky, southern West Virginia and northern West Virginia segments (Gao et al., 2000). The larger basement faults found within the Rome Trough formed during the Grenville Orogeny rifting stage. During the Late Cambrian, rifting ceased and the area transitioned into a passive margin until the collision of the Taconic Orogeny (Gao et al., 2000).

The Bowling Green Fault Zone consists of multistage anastomosing, high-angle normal, high-angle reverse, and thrust faults. The main fault zone consists of mostly anastomosing faults, whereas the high-angle normal and reverse faults occur 50-300 ft (15-91 m) away from the main faulting zone (Onasch and Kahle, 1991). The Bowling Green Fault Zone is the result of Grenville terrane west verging thrusts overriding rift sediments of the East Continent Rift Basin, also known as the Grenville Front (Onasch, 1995). The high-angle reverse faults parallel strike, and are located on the east side of the main fault zone. In association with the thrust faults, fault bend folds, fault-propagation folds, and imbricated fans are common.

The first stage of anastomosing faults occurred during the Late Ordovician to Early Silurian, in close proximity to the timing of the Taconic Orogeny (Onasch and Kahle, 1991). The next stage of deformation occurred during the Middle Silurian, around the time of the Salinic Orogeny. Stages 3-5 occurred post-Middle Silurian, possibly during the later stages of the Salinic Orogeny or Acadian Orogeny (Onasch and Kahle, 1991). The last stage of deformation is the most debatable in age due to the change in deformation from a high-angle to low-angle thrust faulting. The Alleghanian Orogeny is the most likely cause, but strike on the thrust faults tends to vary 30-90 degrees from

Alleghanian stress (Onasch and Kahle, 1991). Onasch and Kahle (1991) suggested that the Bowling Green Fault Zone coincides with the Grenville Front and is not related to the Paleozoic orogenies forming the fault zone. However, these authors also suggest that the subsequent orogenies caused reactivation of the zone through the creation of the Findlay Arch forebulge and/or orogenic stresses. Ascertaining or refuting the impact that the Paleozoic orogenies had on the structure of Morrow County can aid in a better understanding of the study by Onasch and Kahle (1991).

Similar to Onasch and Kahle (1991), Wickstrom et al. (1992) interpreted the Bowling Green Faulting Zone as a complex fault zone of varying magnitudes with the up-thrown block to the east, and extending from central Hancock County northward through southeastern Michigan (Figure 2). The trend of the fault zone ranges from 334°-354° and has an approximated 500 ft (152 m) of throw across the zone. Seismic profiles show that the Bowling Green Fault is a reverse fault with secondary faulting and folding associated around the faulting zone (Wickstrom et al., 1992). Differing from Onasch and Kahle (1991), Wickstrom et al. (1992) detailed the noticeable secondary fault (Outlet Fault Zone) that stems from the Bowling Green Fault Zone. The Outlet Fault Zone trends northwest-southeast from Wood County to Wyandot County. In Wyandot County, this fault system is well documented due to large quantities of oil and gas being produced along the faulting zone (Wickstrom et al., 1992). Analysis on movement and intersection with the Bowling Green Fault Zone is limited; however, Wickstrom et al. (1992) believed that the Outlet Fault is a large synthetic shear zone that does relate to the Bowling Green

Fault Zone. Vertical displacement ranges from 20 ft to 100 ft (6-31 m) with an undetermined amount of lateral displacement (Wickstrom et al., 1992).

The Midcontinent Keweenawan Rift system is an intracratonic rifting system spanning northwest from Lower Michigan to Lake Superior and from Lake Superior southwest to Central Kansas, occurring in conjunction with the Grenville Orogeny (1.0-1.2 Ga) (Gordon and Hempton, 1986). This rift system was first identified by gravity anomaly highs and lows of basement rock, and then later confirmed with radioisotopic age dating, drilling cores, and seismic surveys (Gordon and Hempton, 1986). Faults associated with the rifting are predominantly normal; however, high angle reverse faults flank the sides of the rift and uplift the central areas into a horst. Strike-slip faults (Keweenawan aged) are to be expected along the transform boundaries of the analomy highs. Gordon and Hempton (1986) proposed that the strain imposed from the Grenville Orogeny caused the strike slip faults to propagate farther into the craton, ultimately forming the Midcontinent Keweenawan Rift system.

Drahovzal et al. (1992) defined a rift complex named the East Continent Gravity High, which is an extension of the Midcontinent Keweenawan Rift system. The East Continent Gravity High spans in a north-south direction covering southwest Michigan to north-central Tennessee and is believed to be 1.0 to 1.2 b.y. old. It crosses the Grenville Front in western Ohio and parallels the front as it trends south. The East Continent Gravity High also includes the Fort Wayne Rift, which is oriented northwest-southeast and spans over northeastern Indiana to central-western Ohio (Drahovzal et al., 1992). In an interpretation differing from Gordon and Hempton (1986), Drahovzal et al. (1992)

believed that the East Continent Rift and the Keweenawan Rift systems were initiated before continent-continent collision of the Grenville Orogeny. Thus, the Grenville Orogeny denotes the termination of East Continent Rifting. Baranoski et al. (2009) proposed that rifting associated with the East Continent Rift System and Fort Wayne Rift was initiated during the 100my Grenville Orogeny. As crustal shortening progressed and Grenville terranes accreted onto Laurentia, the rocks associated with the magnetic lineament marking the Grenville Front were exposed (Baranoski et al., 2009). Progression of Grenville continental collision in eastern Ohio exerted extensive fault-bounded rifting in western Ohio, starting with the Fort Wayne Rift followed by the East Continent Rift System. Stein et al. (2014) proposed that the Midcontinent Rift System formed as part of the rifting of the Amazonia craton from Laurentia, rather than an intracratonic rift system. The Midcontinent Rift System is the product of absent or far-field shortening during Grenville time (Stein et al., 2014). Stein et al. (2017) also proposed that the western Grenville edge fold and thrust belt (Grenville Front) spanning from northern Alabama to northern Michigan is not likely a convergent boundary. These authors believed that there is significant evidence suggesting that the linear gravity anomalies perceived as the Grenville Front are related to the Midcontinental Rift System and not the boundary of Grenville terrane thrusting over rift sediments of the East Continent Rift Basin (Stein et al. 2017).

The Cincinnati and Findlay arches both play a role in altering the structure of Morrow County and the surrounding areas. The deposition of the Illinois and Appalachian basins created enough load on the lithosphere, to uplift the Cincinnati Arch, which separated the two basins. The same process occurred with the Michigan and Appalachian basins, and the development of the Findlay Arch (Quinlan and Beaumont, 1984). The deformation associated with Cincinnati Arch uplift is more indirect than the Findlay Arch in Morrow County, as the Findlay Arch is directly west of Morrow County. These two arches uplifted as the Paleozoic orogenies occurred in conjunction with basin subsidence and deposition of sediments (Quinlan and Beaumont, 1984).

Shafer (1989) proposed that the Appalachian Basin compressional tectonism supports the idea of en-echelon strike-line, normal faults being terminated by transverse dip-slip adjustment faults. He also noted that horst-graben structural relationships should be expected in Morrow County. Additionally, Shafer (1989) investigated the paleo-geomorphic surface of the Knox Unconformity (Copper Ridge Dolomite, Trempealeau) to locate the erosional patterns and pre-existing basement controlled joint and growth fault systems. The erosional patterns indicated “U” and “V” shaped valleys, likely from glaciation, at the fault and joint trace locations. Based on the seismic data, the joints and growth faults emanate from basement, and bedrock planes of weakness, and joints and growth faults control pre-glacial topography.

7 STRATIGRAPHY

The Cambrian-Ordovician strata are the main focus of this study (Figure 4). Basement rock consists of Grenville-aged metamorphic rocks. Most of the Cambrian strata were deposited during a passive margin tectonic setting with Morrow County located in a shallow marine setting along the margins of the Iapetus Ocean (Ettensohn, 2008). The Ordovician strata were deposited in a shallow marine setting with some clastic influx from the Taconic Highlands (Ettensohn, 2008). The most targeted producing reservoir within Morrow County is the Copper Ridge Dolomite within the Upper Knox Group.

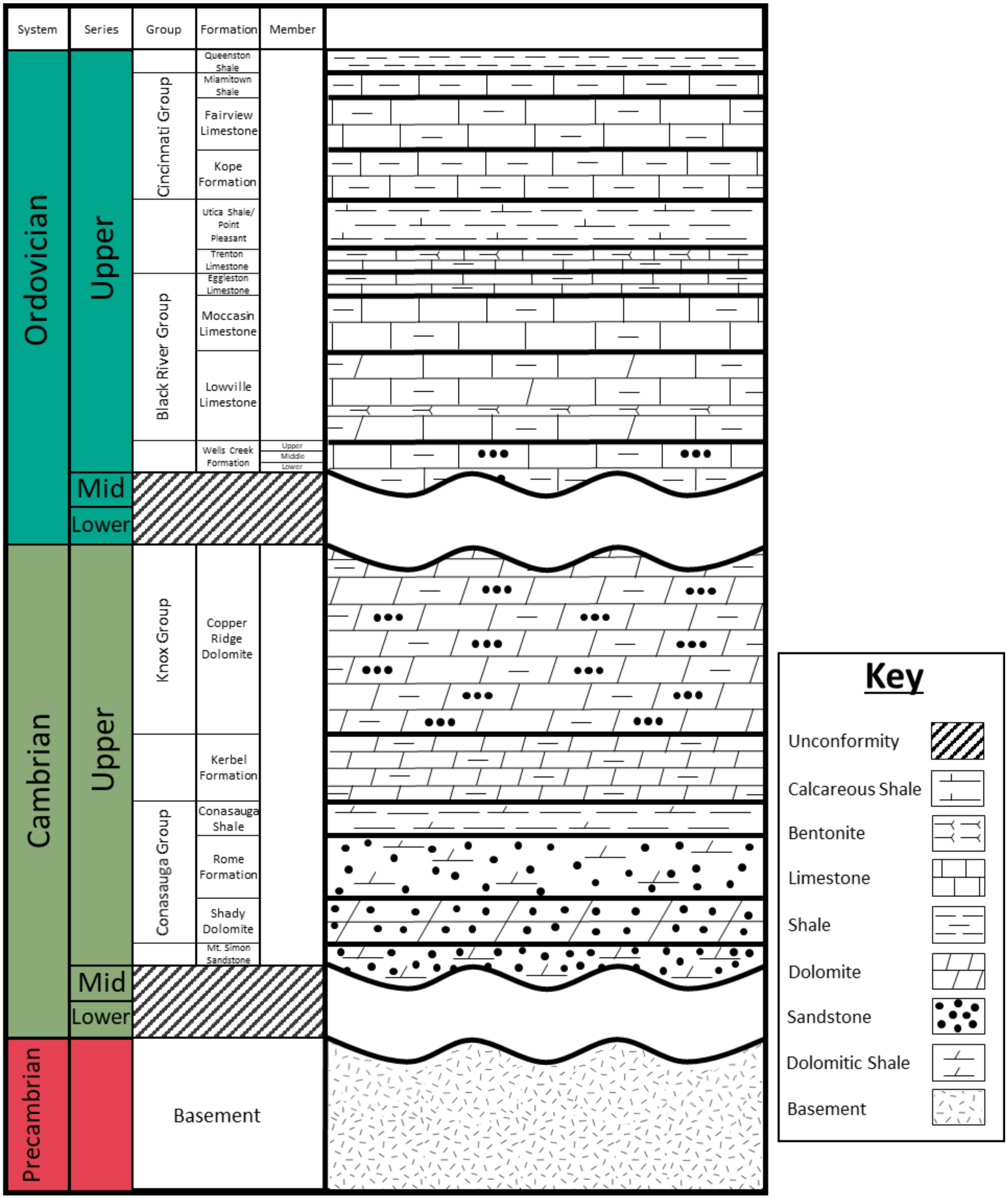

Figure 4. Stratigraphic column of the Cambrian and Ordovician strata in Morrow County, Ohio.

7.1 CAMBRIAN STRATA

Copper Ridge Dolomite (Knox Group)

The Copper Ridge Dolomite conformably overlies the Maynardville Dolomite and consists of 140-250 ft (43-76 m) of white-tan, medium-crystalline, vuggy dolomite interbedded with green-gray, glauconitic siltstone. The lowest member of the Copper Ridge is composed of gray, sparsely cherty, argillaceous limestone. The middle member consist of large quantities of white-gray chert. The upper member resembles the lower units but is more porous due to pre-Ordovician weathering. The post-Knox unconformity tops the Copper Ridge and is overlain by the Ordovician Wells Creek Formation (Wharton, 1964).

Knox Unconformity

The Knox Unconformity is widely traced throughout the extent of the Appalachian Basin and separates the Sauk and Tippecanoe sequences. Lower Ordovician and Upper Cambrian rocks have been truncated by erosion creating the regional remnant doming within the Copper Ridge Dolomite (Wharton, 1964).

7.2 ORDOVICIAN STRATA

Wells Creek Formation

The Wells Creek Formation unconformably overlies the Copper Ridge Dolomite and consist of three different lithostratigraphic members (Lower, Middle, Upper). The

60-foot (18 m) lower member is composed of siltstone, shale, and limestone with sporadic dolomite. There are also conglomeratic layers consisting of granules and reworked Copper Ridge Dolomite clasts. The carbonates are white, dense, and interbedded with glauconitic shales and siltstones. The 10-60 foot (3-18 m) middle member consist of white-tan, dense limestone with some calcite crystals. The 50-foot (15 m) upper member of the Wells Creek consists of brown, dense, argillaceous dolomitic limestone with interbedded shales (Wharton, 1964). The three members have distinct lithological boundaries that are easily observed on the gamma and neutron log, allowing for determination of underlying structure that could influence lithofacies deposition. Furthermore, the lower member of the Wells Creek is useful for identifying remnant domes of the Copper Ridge Dolomite because this member was the first unit deposited onto the subaerially exposed and eroded Copper Ridge Dolomite. Thick areas of the lower member indicate a karst "sink hole" or topographic low, and thin areas indicate a remnant of the underlying dolomite.

Black River Group

The Lowville Limestone conformably overlies the Wells Creek Formation and consists of 340 ft (104 m) of white-tan-gray, dense, finely crystalline limestone, with scattered calcite crystals, sparse bentonite, and pyrite. There are some interbedded argillaceous and dolomitic zones (Wharton, 1964).

The Moccasin Limestone conformably overlies the Lowville Limestone and consist of 110 ft (34 m) of dense, tan limestone. The basal 20-30 foot (6-9 m) unit is a brown, dense, argillaceous limestone with interbedded shales. The overlying 80-90 ft (24-27 m) consist of dense, white-tan limestone with minor amounts of calcite crystals, pyrite, and bentonite (Wharton, 1964).

The Eggleston Limestone conformably overlies the Moccasin Limestone and consist of 40-50 ft (12-15 m) of light tan, dense, limestone with translucent brown chert and interbedded bentonitic black shale (Wharton, 1964).

Trenton Limestone

The Trenton Limestone conformably overlies the Eggleston Limestone and consist of 30-40 ft (9-12 m) of white-tan, coarse to medium crystalline, argillaceous and fossiliferous limestone with sparse brachiopods and bryozoans (Wharton, 1964). There are interbedded, thin, gray or black shales and bentonite layers commonly throughout the formation (Wickstrom and Gray, 1988).

Point Pleasant Formation/Utica Shale

The Point Pleasant Formation/Utica Shale conformably overlies the Trenton Limestone and consist of 170-180 ft (52-55 m) of interbedded light gray to black limestone, brown to black organic-rich calcareous shales, and brachiopod coquina intervals. The Point Pleasant and Utica inter-tongue in part with the Trenton Formation (Ryder, et al., 1992).

Cincinnati Group

The Point Pleasant Formation/Utica Shale is conformably overlain by the Cincinnati Group, which consist of 900 ft (274 m) of interbedded shales, siltstones, and limestones (Wickstrom and Gray, 1988). The Kope Formation is the basal formation of the Cincinnati Group and consist of fossiliferous shales with interbedded sparry limestone (Anstey and Fowler, 1969). The Fairview Limestone is the middle unit, consisting of limestone with interbedded shales, and the Miamitown Shale is the upper unit, consisting of shale and mudstone with thin limestone beds (Ford, 1967).

Queenston Shale

The Queenston Shale conformably overlies the Cincinnati Group and consists of 50-80 ft (15-24 m) of red shale and red sandstone sequences (Ryder, et al., 1992). The overlying Silurian strata are unconformable, as the contact separates deposits of the underlying Tippecanoe and overlying Kaskaskia Sloss sequences.

8 METHODOLOGY

A key objective of this study is to correlate stratigraphic horizons across the county by determining formation boundaries on the Cambrian-Ordovician strata using well logs. The dataset discussed herein includes logs from 2,662 wells in Morrow County that were uploaded into Petra (IHS). Each well included, at a minimum, gamma-ray and neutron logs that were depth registered and able to be correlated with stratigraphic horizons. Formation boundaries for the 2,662 wells were determined for all Cambrian-Ordovician strata based upon the type log (Figure 5) (Calvert, 1964). Depths were then exported into the Kingdom Suite (IHS) for structure mapping, isopach mapping, and trend surface analysis. The targeted producing reservoir within Morrow County is the Copper Ridge Dolomite within the Upper Knox Group. There were only ten wells that were logged deeper than this reservoir. Therefore, mapping on the Mount Simon Sandstone, Conasauga Group, and Kerbel Formation did not have enough spatial resolution to determine structural features within the formations.

IHS Markit offers a multitude of databases and software's to maximize geological interpretations. In this study IHS Petra and Kingdom were used. IHS Petra is a geological software for well log analysis only, and IHS Kingdom is a geological software for seismic and well log analysis.

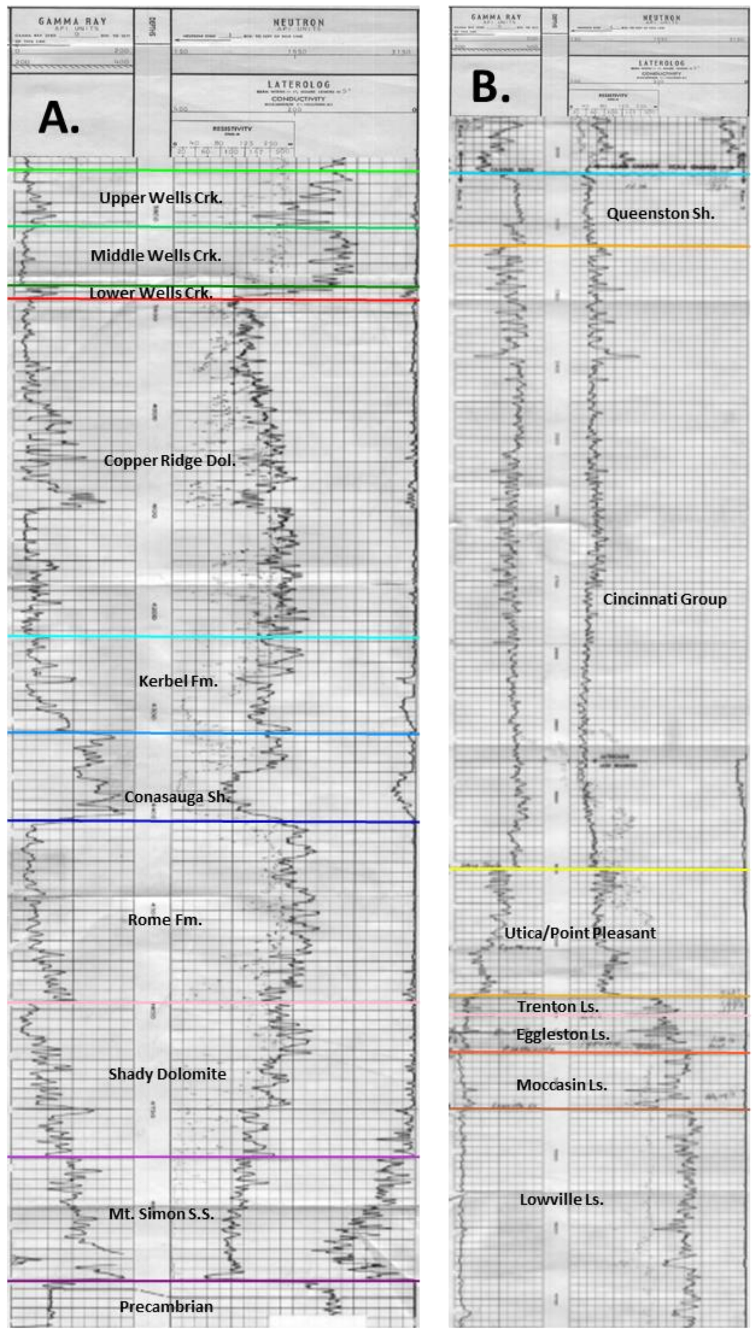

Figure 5. Type log (API: 34117200470000) A) From TD (4,890 ft or 1490 m) to 3,700 ft (1128 m) MD, marking the Precambrian to Upper Wells Creek; B) From 3,700 ft to 2,100 ft MD (1128-640 m) measured depth, marking the Lowville Limestone to Queenston Shale (Calvert, 1964).

A structure map is subsurface map in which the contours represent the elevation (subsea) of a formation or geologic marker in space. Structure maps were created using the subsea formation boundary depths and contoured through simple kriging in Kingdom. Kriging is a stochastic spatial interpretation method that creates a continuous prediction surface based upon subsea elevation points (formation boundaries) (ArcMap, 2016). Simple Kriging is a variation of kriging that averages the subsea elevation points to create a simpler continuous prediction surface (IHS Markit, 2020). Once these data points were mapped, the data was analyzed for outliers by observing irregular data points. The outliers were reexamined for miss-picks and log quality, and if either of these proved to be an insufficient data point, the data was filtered.

An isopach map is a map in which the stratigraphic thickness of a rock is displayed. To create isopach maps, a well query on the formation boundaries was needed for each formation boundary of interest. The well query needed the overlying and underlying formation boundary to find the thickness of the formation. Once each well query was created for the formation boundaries, using Kingdom Suite (IHS), the isopach maps were created by subtracting the underlying formation structure map (continuous prediction surface) from the overlying formation structure map (continuous prediction surface) resulting in the overlying formation's isopach (thickness).

Trend surface analysis was then conducted on the structure maps at each formation boundary to replicate the regional structural trend of the Appalachian Basin. The regional trend of the Appalachian Basin is represented by deepening to the east and gradual shallowing to the west. Trend surface analysis is a spatial interpolation method that depicts a general trend (in this study, Appalachian Basin trend) on each formation boundary structure map that was created using simple kriging. This trend surface mapping process was completed through Kingdom Suite (IHS). Deviations from this trend are likely the results of structural features, such as faults or regional remnant karst domes that are found within the Copper Ridge Dolomite. A 4^{th} order polynomial trend closely replicated the regional Appalachian structural trend (dip). 1^{st} and 2^{nd} order polynomial trends under represented regional trend because regional dip was too shallow, and 5^{th} order polynomial trend or greater over represented the regional structural trend (dip). Residual maps illustrate the difference between two interpolated surfaces, the structure map (kriging) and the trend surface map. A residual map was then created to determine deviations from the regional trend and to locate anomalous features. The residual maps were calculated by subtracting the structural trend from the formation boundaries (structural contour map) in Kingdom, resulting in positive or negative deviations in the trend reported in feet. These anomalous highs and lows could indicate a structural feature, in this case a potential fault or remnant dome. Here, the residual maps were visually assessed in conjunction with the isopach map and lithofacies description to determine “lineaments” or remnant domes. The structural features were then confirmed by verifying the formation boundary locations, well placement locations, and surface elevations to ensure data quality. All lineament and remnant dome polygons were visually identified based upon geologic interpretations and were digitized by the author. Full details on trend surface can be found in Mei (2009).

9 RESULTS

Throughout the state of Ohio, the known faults and lineaments are primarily oriented in two different directions (Figure 3). The most common orientation trends northwest-southeast and the secondary orientation trends northeast-southwest (Figure 3). Within Morrow County specifically, there are two lineaments previously defined by Solis (2015) that are northwest-southeast trending in the northeastern part of Morrow County (Figure 3) and align with two mapped lineaments from this study (Figure 6; lineament 5 and 9). The term lineament is used in reference to “inferred faults” – that is, there appears to be a linear disruption to the structure of the formation, along with thinning or thickening coinciding with the location. Without 2D or 3D seismic data profiles to verify if these are indeed faults, and determine their relative directions of movement, these features will be referred to as “lineaments” throughout this manuscript, and interpreted as faults with inferred directions.

Overall, nine lineaments trending in the northwest-southeast orientation and five lineaments trending in the northeast-southwest orientation were identified in this study (14 in total). These lineaments were determined by assessing the structure residual maps of the lower member of the Wells Creek and overlying formations, as residuals in the Copper Ridge Dolomite are assumed to be remnant domes. These lineaments were visually located by tracing the outlines of highs or lows on the residual maps, and verified and interpreted by observing the isopach maps and lithofacies. The 14 lineaments are consistent throughout all Ordovician strata overlying the Copper Ridge Dolomite, although some lineaments are more prominent (Figure 7-17C). These are discussed below with respect to each unit of interest.

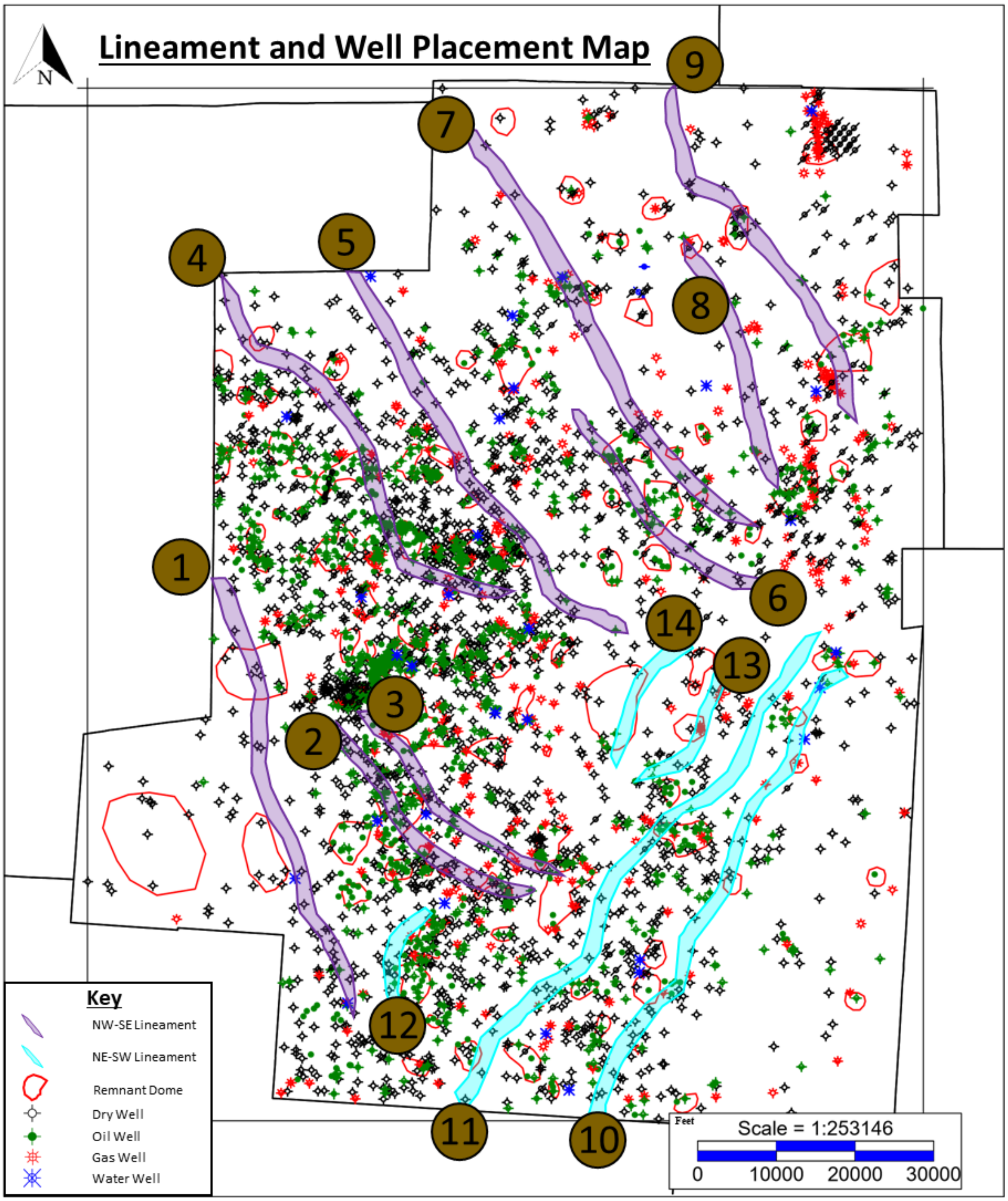

Figure 6. Map of Morrow County, OH showing well locations, interpreted lineaments (blue and purple), which are numbered for reference, and locations of interpreted remnant domes (red outlines).

The Lower Knox, Copper Ridge Dolomite (Trempealeau) consists of remnant doming and other structural deformation throughout Morrow County. The structure contour map displays a regional eastward dipping trend of 0.7 degrees, with numerous domes obvious throughout (Figure 7A). These domes are the result of subaerial exposure during the development of the Knox Unconformity (Dolly and Busch, 1972). The 4^{th} order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 7B). All lineaments flank these domes (Figures 7C), which are located throughout the county, with the highest cluster located in western Morrow County (Figure 7D).

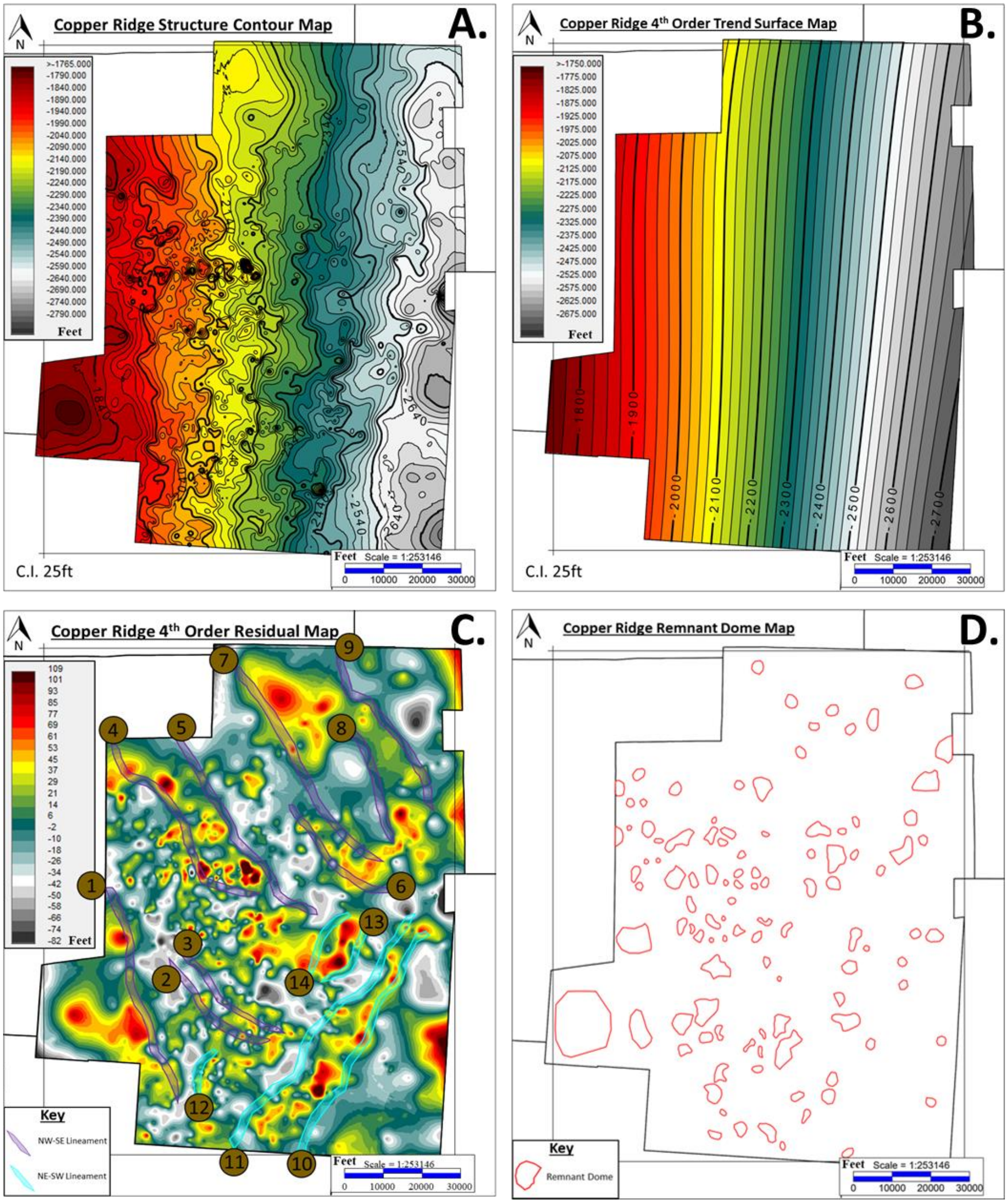

Figure 7. Copper Ridge Dolomite maps (Upper Knox). A) Structure contour map with highly concentric areas representing the remnant doming. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual value (red)) and graben (low residual values (gray/blue)) sequences. D) Outline (red) of every remnant dome in Morrow County.

The lower member of the Wells Creek Formation was the first unit deposited onto the remnant karst features of the Copper Ridge Dolomite, following the development of the Knox Unconformity, and consists of fine-grained siliciclastic sediments. These siliciclastic sediments infilled topographic lows, creating thick areas of this lower member and indicate a karst “sink hole,” whereas thin areas indicate remnant doming of the underlying Copper Ridge Dolomite. The structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees (Figure 8A). The 4th order trend map also indicates a shallow regional dip of 0.6 degrees east (Figure 8B). The residual map varies from (-67) ft to 92 ft (-20 to 28 m), indicating that the structure of the formation varies from the overall trend (regional structure) by (-67) ft (-20 m) to 92 ft (27 m) throughout the county (Figure 8C). Lineaments 1, 4, 6, and 10-14 are traceable on the residual map, with structural highs located within the bounding regions of these lineaments. Near lineaments 1, and 7-9, there are structural highs and lows adjacent to these lineaments. The isopach map shows the formation varying in thickness from 5 to 67 ft (2 to 20 m) in the southeastern section and 2 to 40 ft (1 to 12 m) in the northwestern section. The isopach is highly variable throughout the formation, with thickening along two areas in the southeastern portion of the county (coinciding with lineaments 10 and 11) and a thinning in all hypothesized remnant doming areas (Figure 8D).

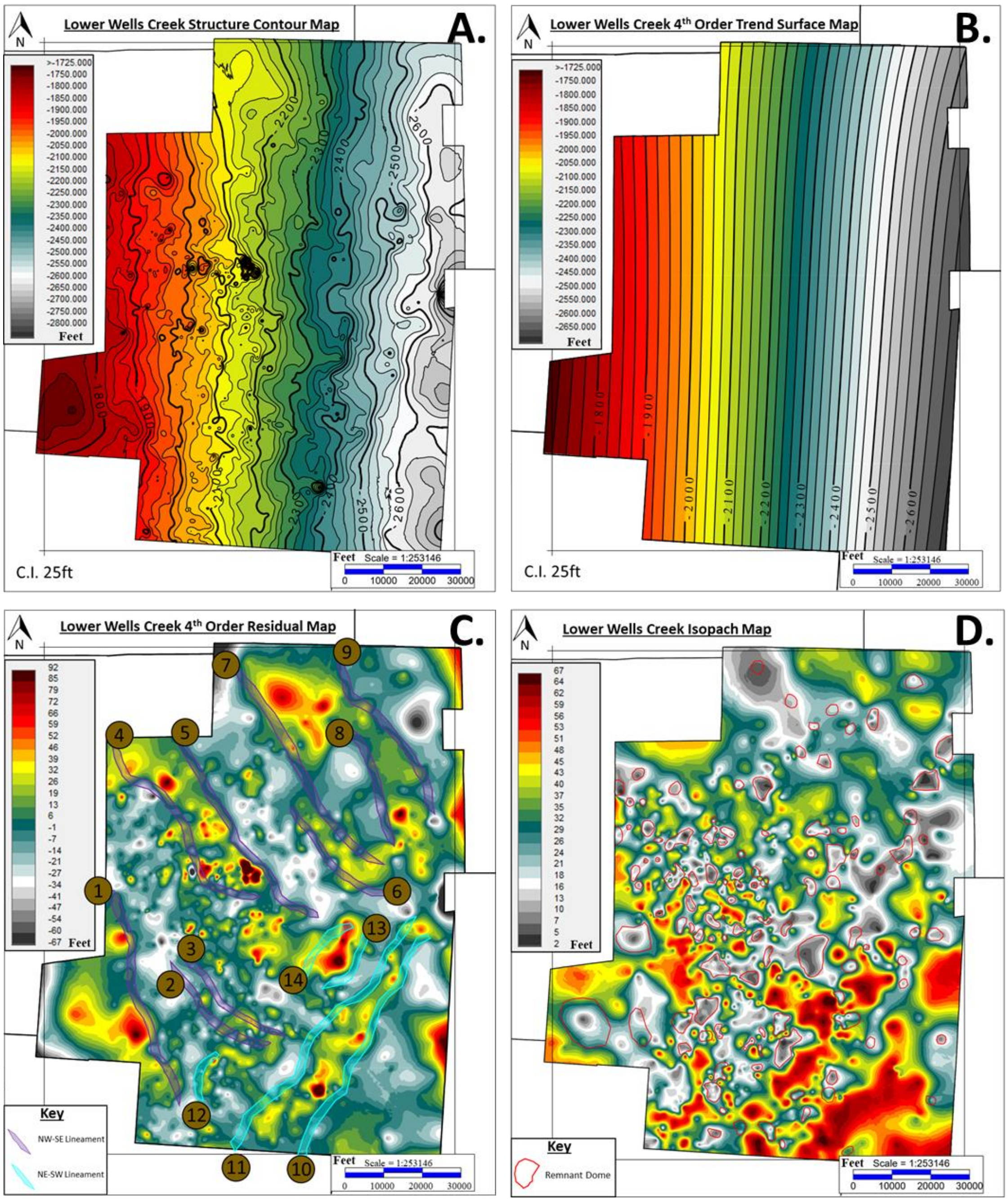

Figure 8. The lower member of the Wells Creek Formation maps A) Structure contour map with highly concentric areas representing possible remnant domes. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map correlated with all remnant domes within Morrow County (domes in red).

The presence of remnant doming began to diminish as deposition of the middle member of the Wells Creek started. The structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees, with the absence of domes (Figure 9A). The 4^{th} order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 9B). The residual map varies from (-70) ft to 75 ft (-21 m to 23 m), indicating that the structure of the formation varies from the overall trend (regional structure) by (-70) ft (-21 m) to 75 ft (23 m) throughout the county (Figure 9C). Lineaments are more prominent in the middle member of the Wells Creek Residual Map, but lineaments 2 and 3 still lack definitive residuals. The isopach map shows the formation varying in thickness from 20 to 62 ft (6 to 18 m) (Figure 9D). The thickness is mostly consistent throughout the formation, with thickening along all lineaments and thinning on the remnant domes.

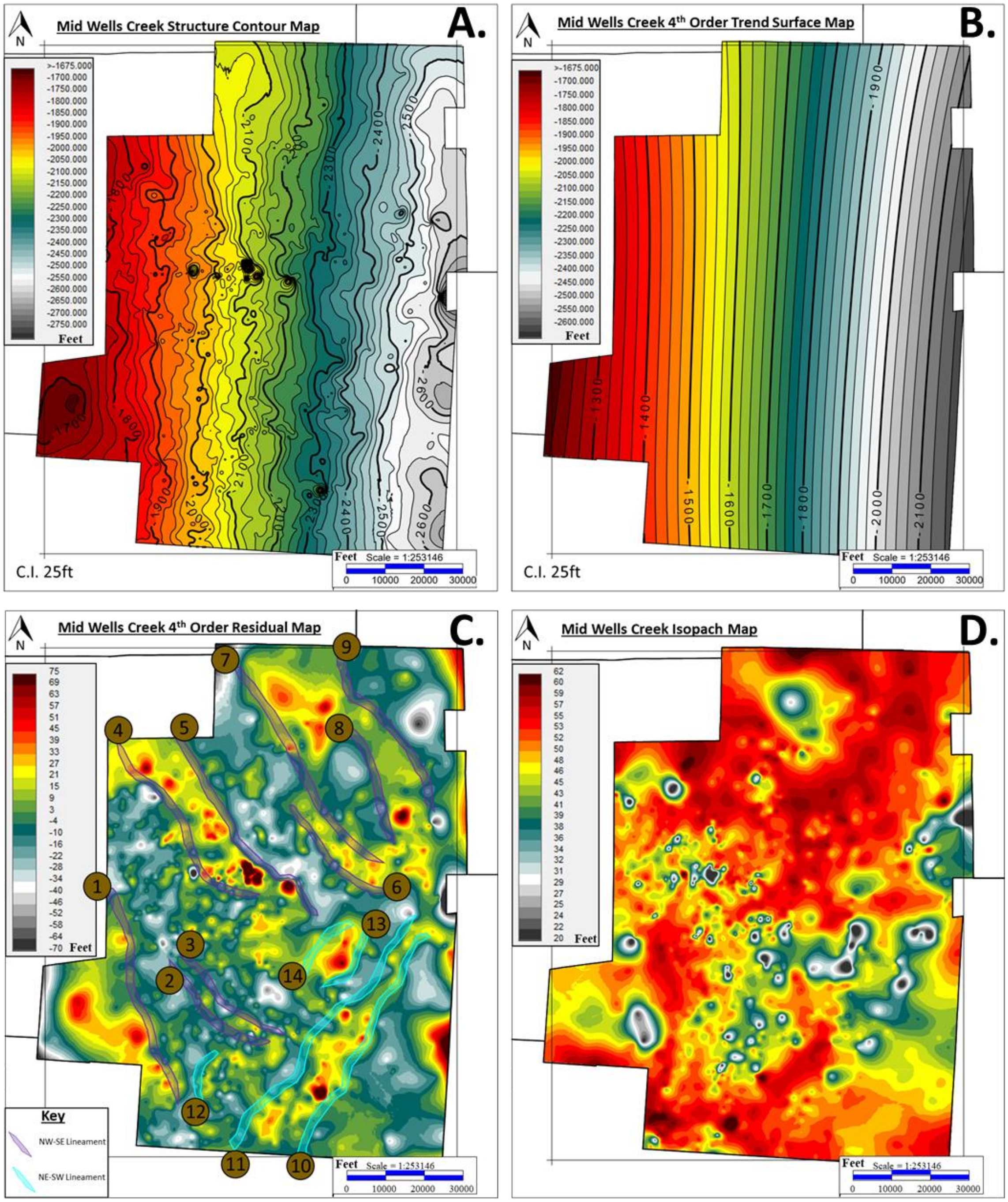

Figure 9. The middle member of the Wells Creek Formation maps A) Structure contour map with highly concentric areas representing possible remnant domes. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map.

The upper member of the Wells Creek structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees and a smoothing of contours (Figure 10A). The 4th order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 10B). The residual map varies from (-68) ft to 70 ft (-21 m to 21 m), (Figure 10C). The isopach map shows the formation varying in thickness from 55 to 67 ft (17 to 20 m) in the eastern and southeastern sections of the county and 49 to 55 ft (15 to 17 m) in the northwestern and western sections of the county. The upper member generally thickens towards the southeast, with thickening along lineaments 6, 7, 10 and 11 and thinning along lineaments 1, 4 and 5 (Figures 10D).

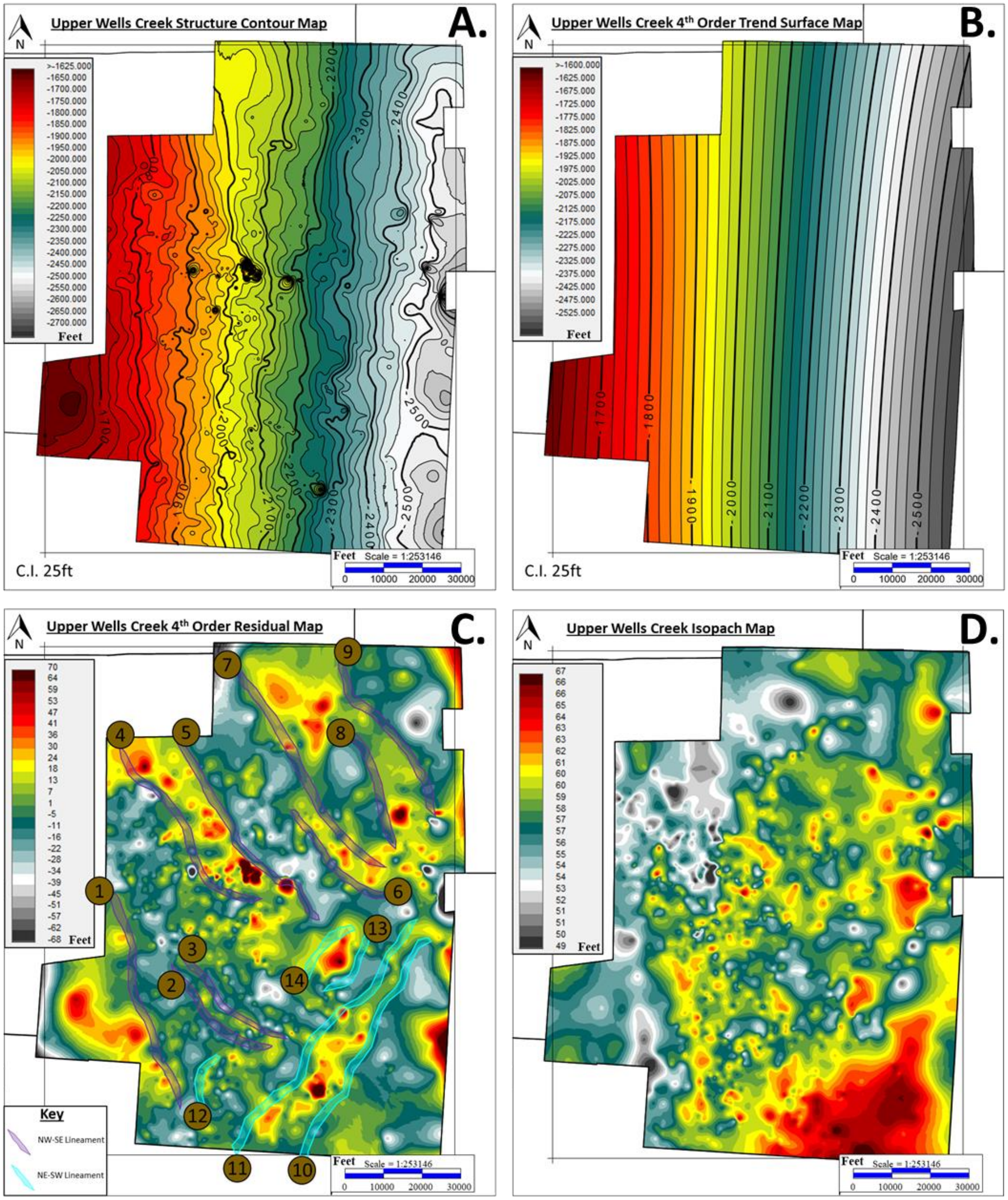

Figure 10. The upper member of the Wells Creek Formation maps A) Structure contour map. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map.

The Lowville Limestone (Black River Group) structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees similarly to the Appalachian Basin (Figure 11A). The 4th order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 11B). The residual map varies from (-60) ft to 65 ft (-18 to 20 m) (Figure 11C). The residual prominence associated with lineaments 2 and 3 is first established in the Lowville Limestone. The isopach map shows the formation varying in thickness from 321 to 338 ft (98 to 103 m) in the eastern and southeastern sections of the county and 306 to 327 ft (93 to 100 m) in the western half of the county. The formation generally thickens toward the east, with thickening along lineaments 5, 8, 9, 10 and 11 (Figure 11D).

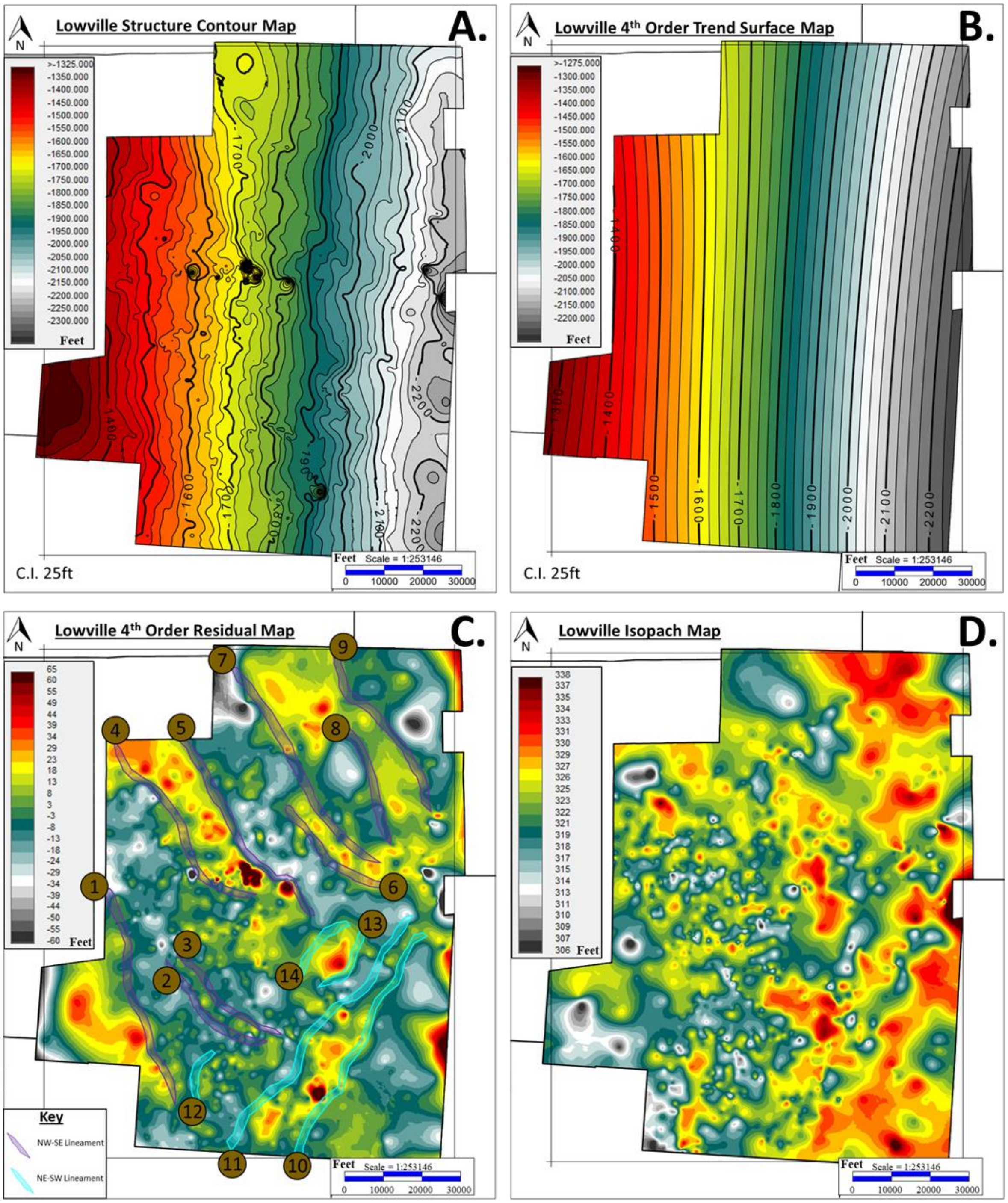

Figure 11. Lowville Formation (Black River Group) maps A) Structure contour map. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map.

The Moccasin Limestone (Black River Group) structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees, with some contours indicating structural features (Figure 12A). The 4th order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 12B). The residual map varies from (-62) ft to 66 ft (-19 to 20 m) (Figure 12C). The isopach map shows the formation varying in thickness from 78 to 83 ft (24 to 25 m) in the eastern half of the county and 71 to 77 ft (22 to 23 m) in the western half. The Moccasin Limestone generally thickens toward the northeast and southwest, with thickening along lineaments 8 and 9 and thinning along lineaments 1, 2, 3 and 4 (Figure 12D).

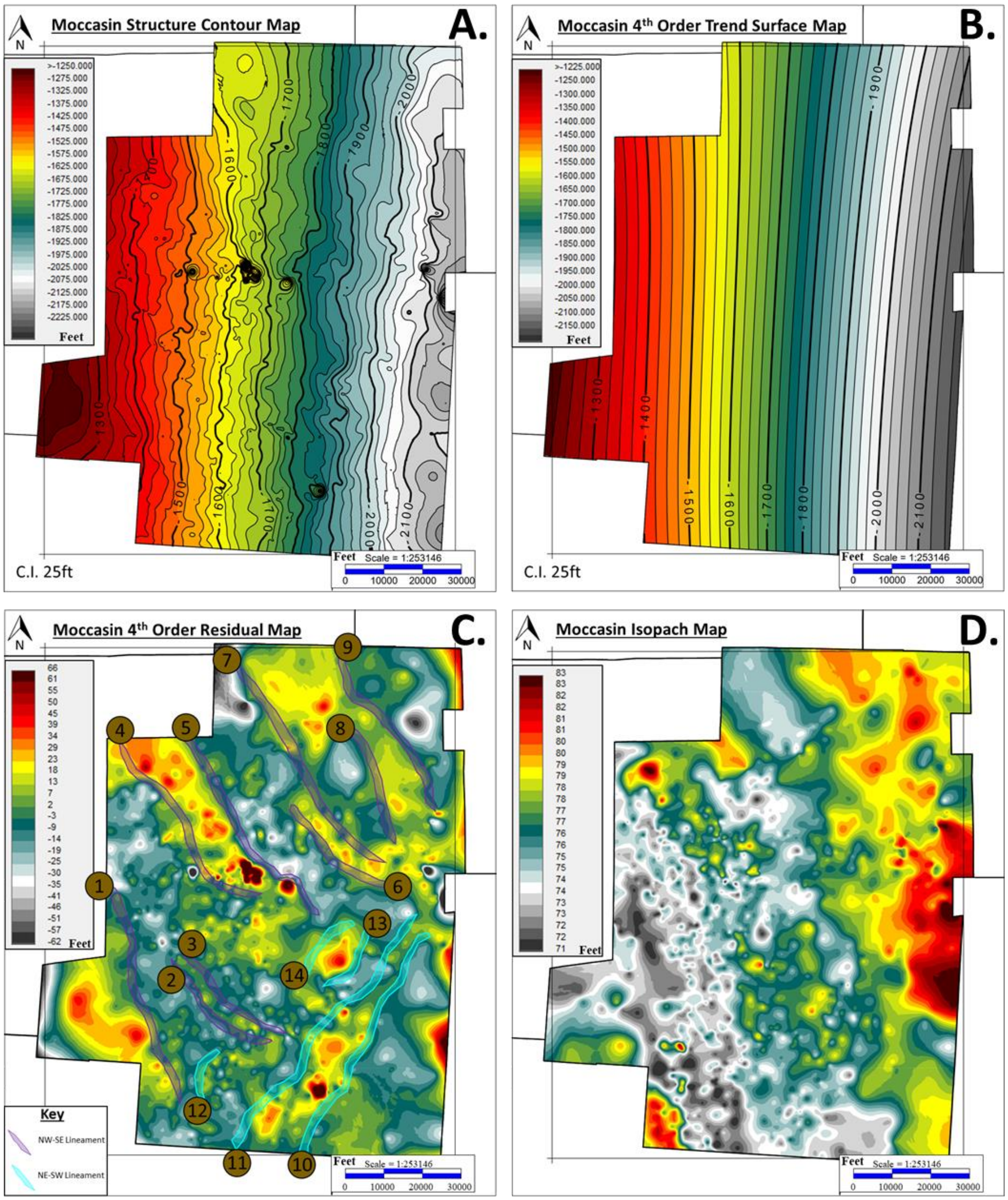

Figure 12. Moccasin Limestone (Black River Group) maps A) Structure contour map. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map.

The Eggleston Limestone (Black River Group) structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees similarly to underlying formations (Figure 13A). The 4th order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 13B). The residual map varies from (-61) ft to 70 ft (-19 to 21 m) (Figure 13C). The northern portion of lineaments 10 and 11 have a decrease in residual values. The isopach map shows the formation varying in thickness from 41 to 48 ft (13 to 15 m) in the southwestern corner of the county and gradually thickening to the northeast to thickness of 50 to 56 ft (15 to 17 m). The formation generally thickens toward the east - northeast, with thickening along lineaments 4 and 5 and thinning along lineament 1 (Figure 13D).

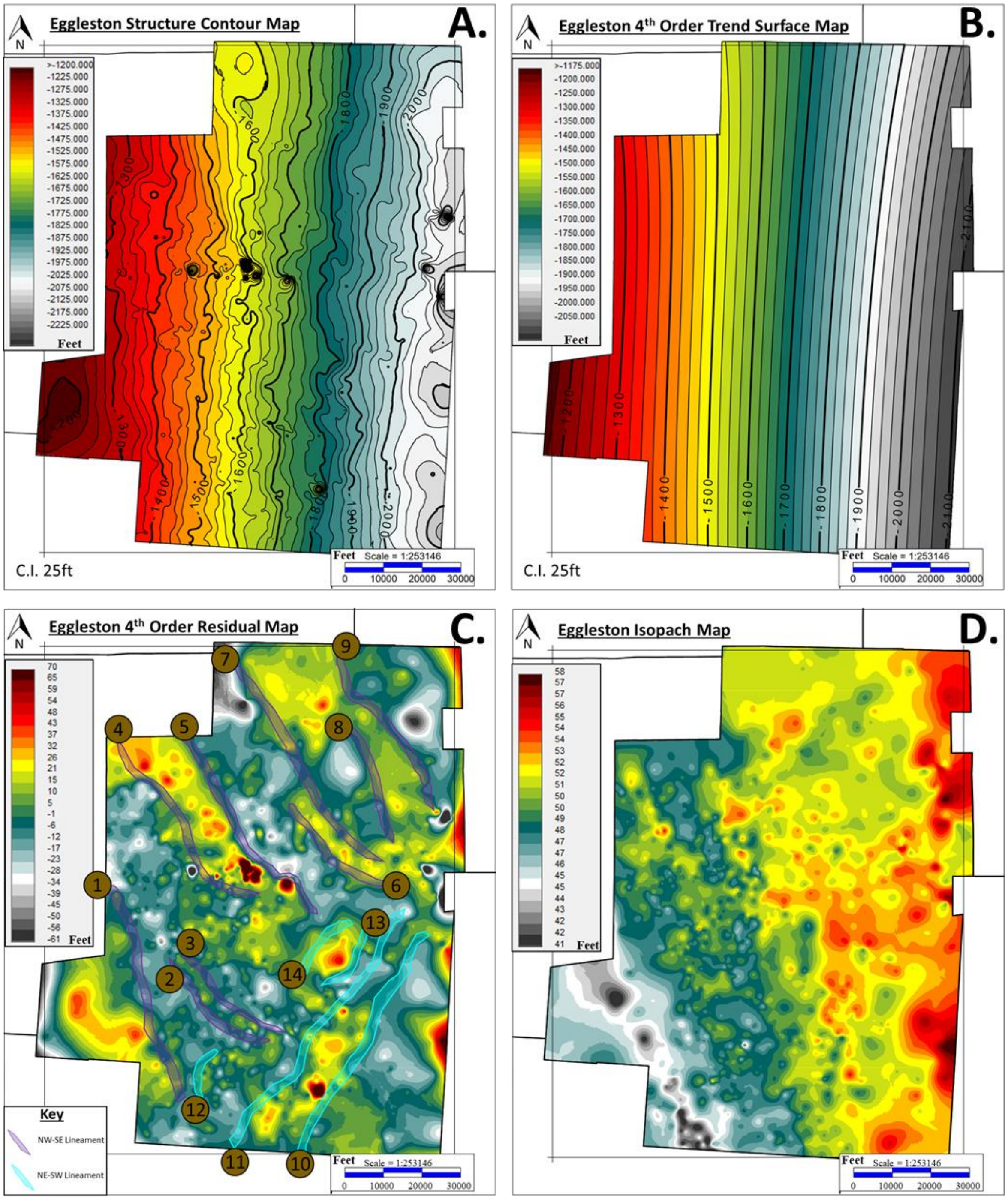

Figure 13. Eggleston Limestone (Black River Group) maps A) Structure contour map. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map.

The Trenton Limestone structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees (Figure 14A). The 4th order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 14B). The residual map varies from (-61) ft to 69 ft (-19 to 21 m) (Figure 14C). The northern portion of lineaments 10 and 11 have a decrease in residual values. The isopach map shows the formation varying in thickness from 24 to 29 ft (7 to 9 m) in Morrow County, with no direct correlation to any lineaments (Figure 14D).

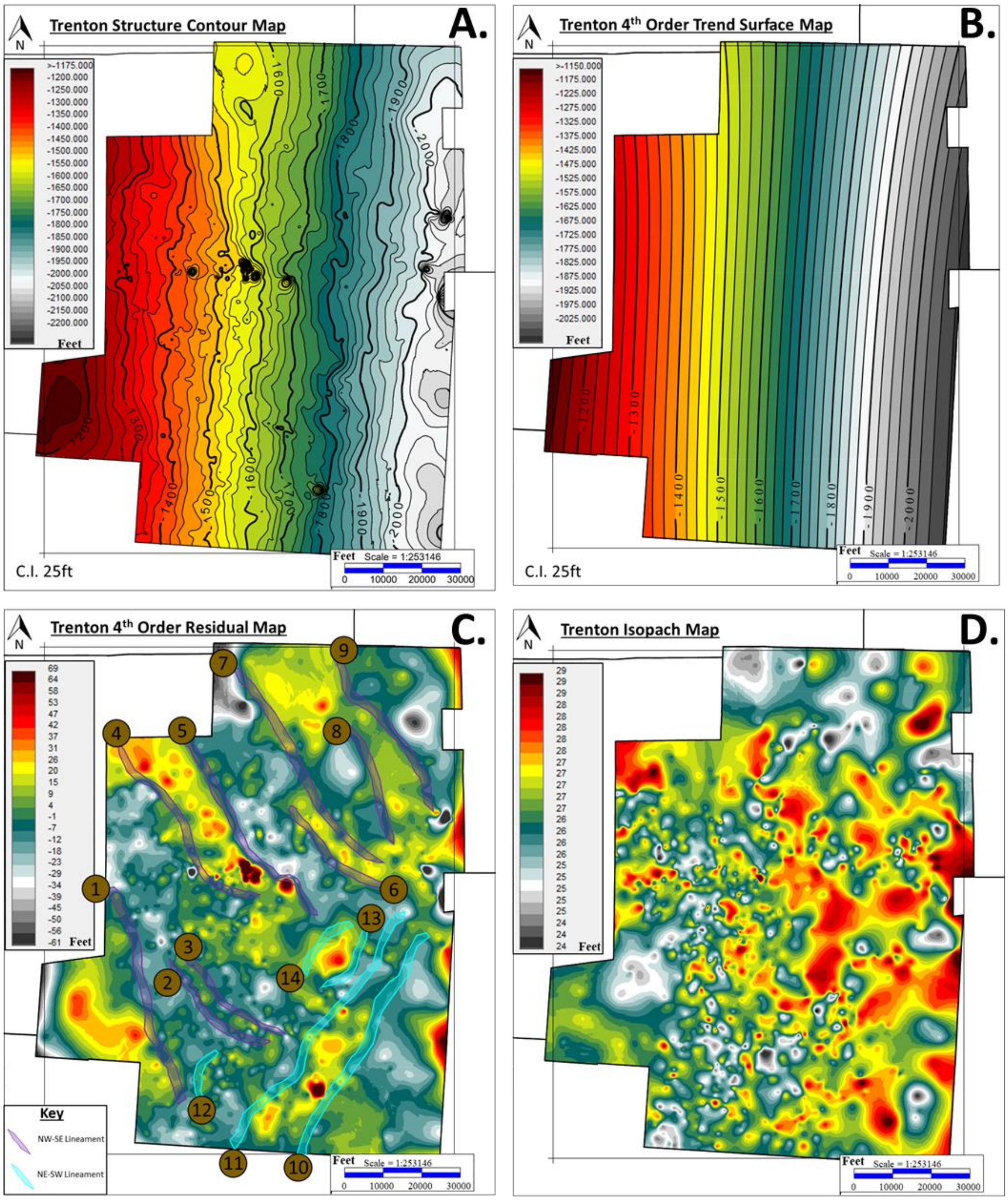

Figure 14. Trenton Limestone maps A) Structure contour map. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map.

Similar to the Trenton and underlying formations, the Utica/Point Pleasant structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees (Figure 15A). The 4th order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 15B). The residual map varies from (-70) ft to 65 ft (-21 to 20 m) (Figure 15C). The isopach map shows the formation varying in thickness from 168 to 181 ft (51 to 55 m) in the northwestern half of the county and 181 to 189 ft (55 to 58 m) in the east-southeastern half. The Trenton Limestone generally thickens toward the east-southeast, with thickening between lineaments 8 and 9 (Figure 15D).

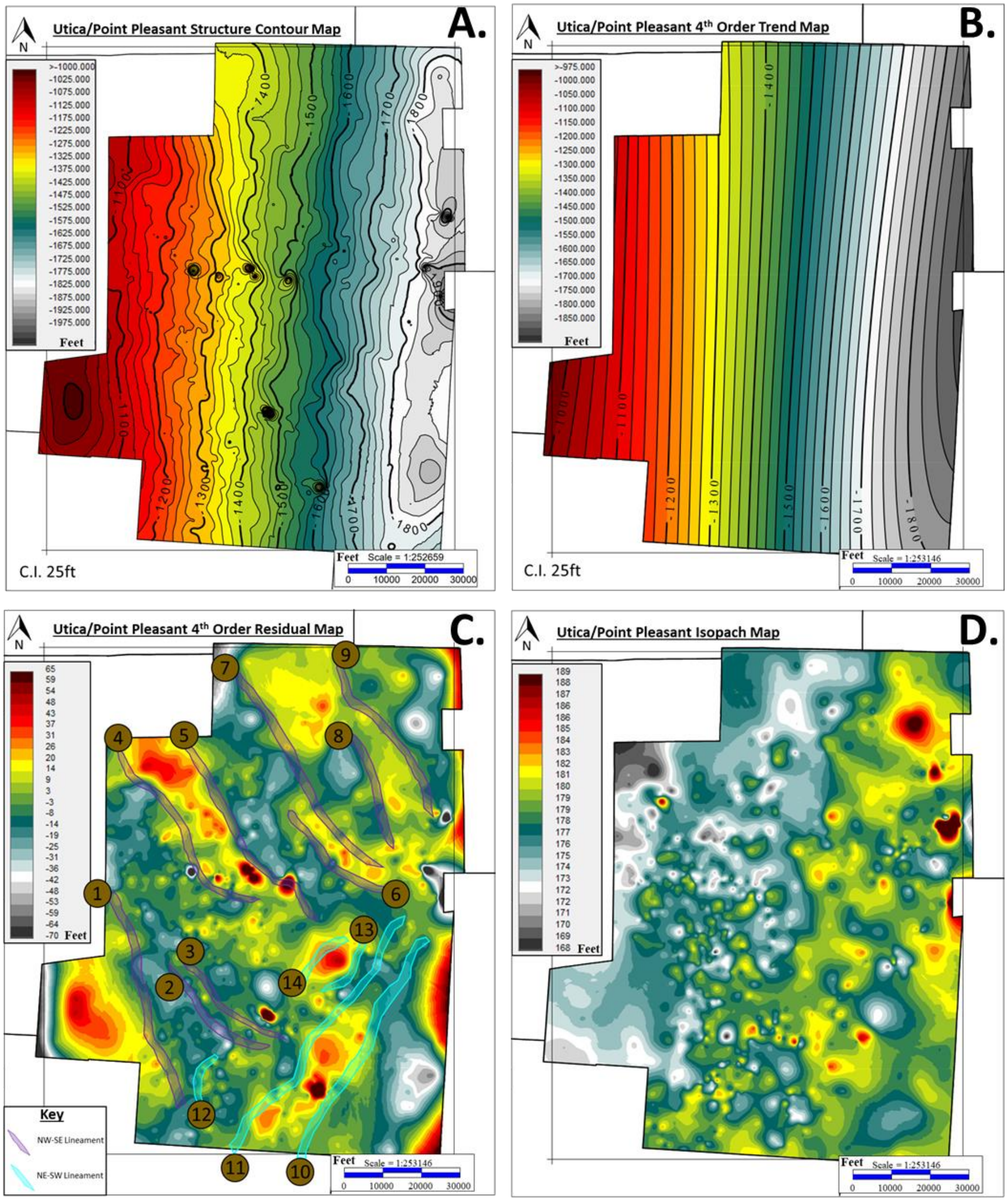

Figure 15. Utica/Point Pleasant Formation maps A) Structure contour map. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map.

The Cincinnati Group structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees (Figure 16A). The 4^{th} order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 16B). The residual map varies from (-67) ft to 58 ft (-20 to 18 m) (Figure 16C). The isopach map shows the formation varying in thickness from 823 to 863 ft (251 to 263 m) in the western half of the county and 874 to 911 ft (266 to 278 m) in the eastern half. The Cincinnati Group generally thickens toward the east, with no direct correlation to the lineaments (Figure 16D).

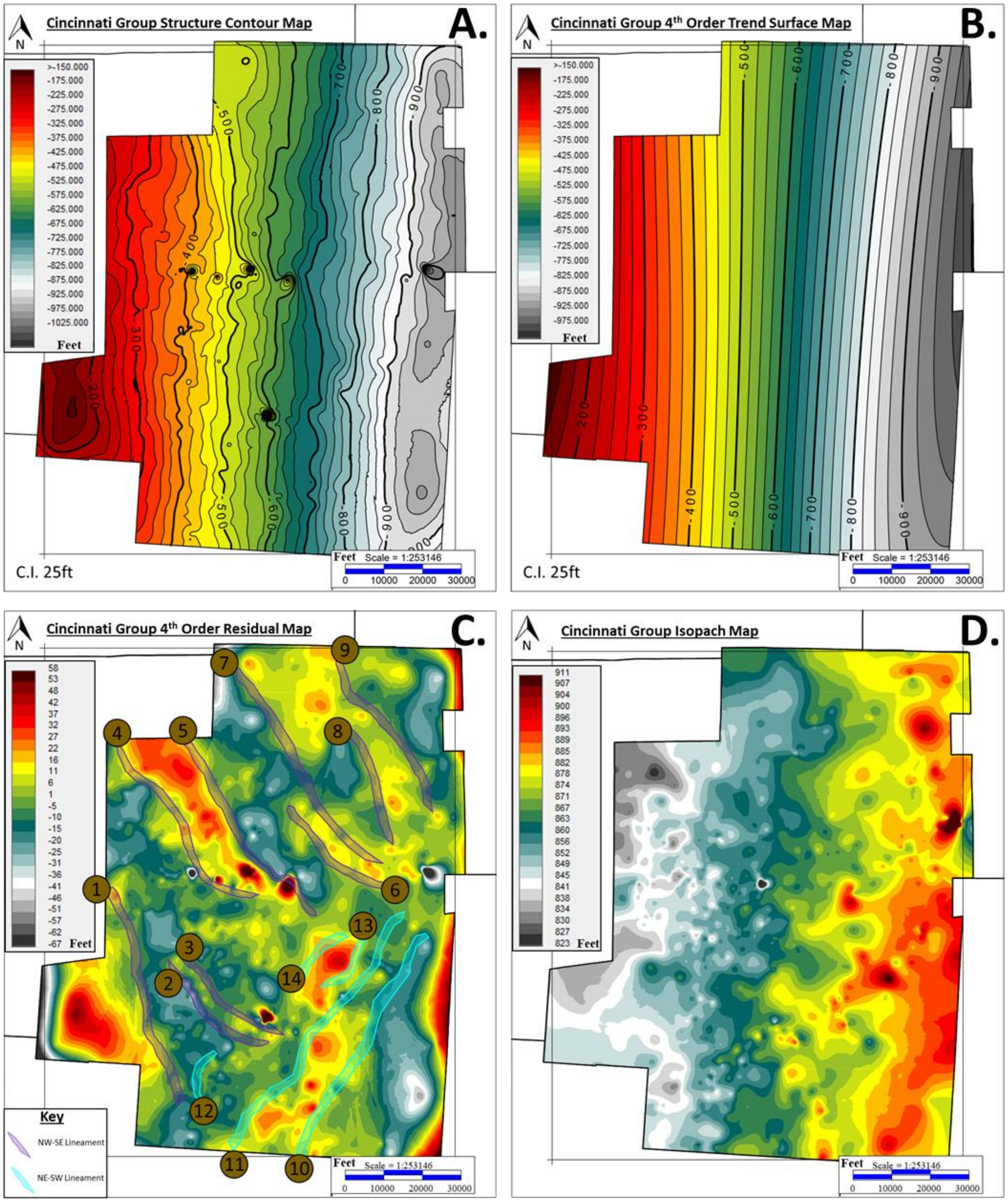

Figure 16. Cincinnati Group maps A) Structure contour map. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map.

The Queenston Shale structure contour map displays the regional eastward dipping trend of approximately 0.6 degrees (Figure 17A). The 4^{th} order trend map also indicates a shallow regional dip of 0.6 degrees east (Figures 17B). The residual map varies from (-65) ft to 54 ft (-20 to 17 m) (Figure 17C). The isopach map shows the formation varying in thickness from 85 to 103 ft (26 to 31 m) in the southwestern half of the county and 104 to 114 ft (32 to 35 m) in the northeastern half. The thickness is variable throughout the formation, with thickening in lineaments 8 and 9 (Figure 17D).

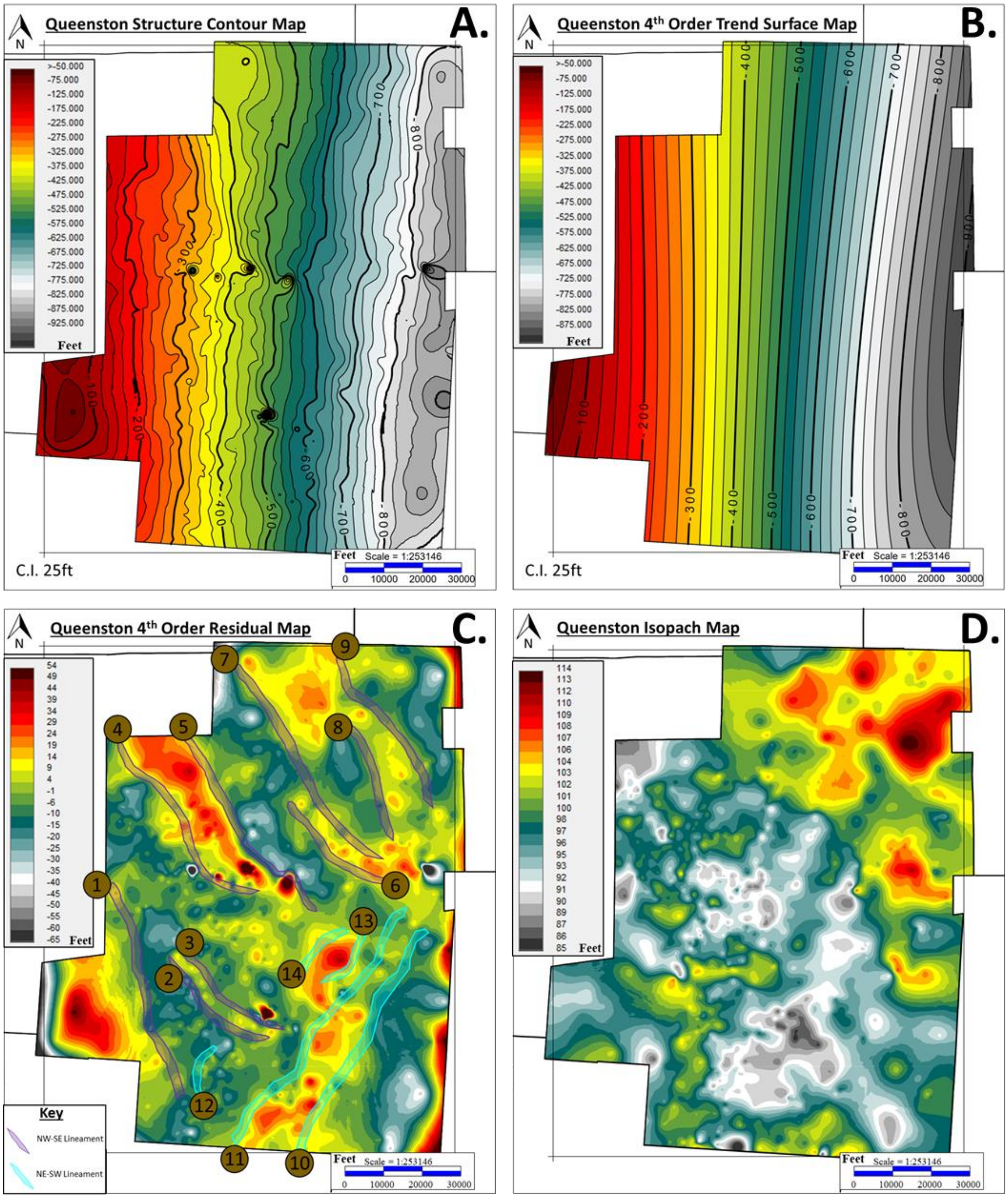

Figure 17. Queenston Shale maps A) Structure contour map. B) 4th order trend surface map. C) 4th order residual map with numbered lineaments outlined along horst (high residual values (red)) and graben (low residual values (gray/blue)) sequences. D) Isopach map.

Although 14 lineaments are consistent throughout all Cambrian Ordovician strata, the residual values vary to some extent. Lineament 1 bounds the western most area of Morrow County. West of lineament 1 has a residual range of 53 to 85 ft (16 to 26 m), and east of lineament 1 ranges from (-58) to -10 ft (-18 to -3 m) throughout the maps, suggesting a high area to the west and low area to the east. Lineaments 2 and 3 are not easily visible on the Copper Ridge residual map (Figure 7C) because of the noticeable remnant doming, but have residual ranges of 4 to 14 ft (1 to 4 m) on the apparent high and (-15) to -1 ft (-5 to -0.3 m) on the low sides. Lineaments 4 and 5 bound an apparent high in the northwestern portion of Morrow County. The apparent high ranges in residual values of 37 to 109 ft (11 to 33 m), and the bounding lows range from (-50) to (-18) ft (-15 to -6 m). Lineament 6 residual values range from (-50) to -2 ft (-15 to -1 m) on the southwest side and 37 to 61 ft (11 to 19 m) on the northeast side. The southern portion of lineament 7 bounds an apparent high on the southwestern side and the northern portion bounds an apparent high on the northeastern side. The apparent highs have a residual range from 26 to 72 ft (8 to 22 m) and the apparent lows range from (-47) to -7 ft (-14 to -2 m). Lineament 8 bounds an apparent high to the northeast ranging from 6 to 92 feet (2 to 28 meters) and an apparent low to the southwest ranging from (-34) to -7 ft (-11 to -2 m). The apparent high associated with lineament 9 is located on the southwestern side with a residual range of 6 to 92 ft (2 to 28 m) and the apparent low is located on the northeast side with residual ranging (-10) to (-64) ft (-3 to -20 m). Lineaments 10 and 11 bound an apparent high in the southeastern portion of Morrow County. The apparent high, ranges in residual values of 9 to 109 ft (3 to 33 m) and the bounding lows, range from (-50) to (-18) ft (-15 to -6 m). Lineament 12 bounds an apparent high on the southeast with residual ranging from 29 to 61 ft (9 to 19 m) and an apparent low on the northwest with residual ranging from (-34) to (-58) ft (-10 to -18 m). Lineaments 13 and 14 bound an apparent high in the central portion of Morrow County. The apparent high, ranges in residual values of 61 to 109 ft (19 to 33 m) and the bounding lows, range from -35 to (-3) ft (-11 to -1 m).

All fourteen lineaments extend through the Cambrian Ordovician strata and are believed to extend down into the Grenville Basement. These lineaments also likely extend upsection into Silurian strata, because they are still prevalent as they extend into the Queenston Shale, the uppermost formation in this study, and previous mapping has suggested multiple reactivations throughout each subsequent orogeny (Solis, 2015; Ohio Division of Geological Survey, 2020). Due to remnant doming, the Copper Ridge structure contour map and the lower member of the Wells Creek structure contour map are the only structure contour maps indicating two types of structure: lineaments and domes. However, the fourth order trend surface maps for all the strata are very similar, with all the formations having varying thicknesses that appear to correspond to lineament locations, other than the upper part of the Black River Group and the Trenton Limestone. The isopach maps indicate that these faults were active pre- or syn-deposition.

10 DISCUSSION

The goal of this research was to evaluate the underlying structure and potential reactivation history within the county, and to determine if lineaments influenced hydrocarbon production trends. The conventional understanding for production in Morrow County is the remnant doming found throughout the Copper Ridge Dolomite (Knox), however there is little understanding of specific fault locations and their impact on production and migration into the reservoir. Based upon orientation, thickness changes, and orogenic events, there are 14 lineaments that are interpreted to be faults, trending either northwest-southeast or northeast-southwest, creating two horst and graben sequences. These faults have reactivated throughout time with various orogenic events, creating topographic highs and lows, and affecting deposition of sedimentary sequences.

10.1 REMNANT DOMES

Within the Copper Ridge Dolomite structure map there are numerous domes that can be delineated throughout the county (Figure 7A). These domes are also recognizable on the lower member of the Wells Creek isopach map, indicated by thinning (low residual value (black)) of this fine-grained, siliciclastic formation over the paleo-topographic highs and adjacent thickening (Figure 8D). These domes are the result of mass erosion within the Knox Dolomite after being subaerially exposed by a eustatic regression in sea level and uplift of the Waverly Arch in Central Ohio (Root and Onasch, 1999). During this time of mass erosion (Early-Middle Ordovician, lasting 20-35 my), sediment was being transported from the Canadian Craton from the northwest and drained into the Iapetus Ocean towards the southeast (Blakey, 2013). In Morrow County, the remnant domes parallel the lineaments, which suggests that during this erosional event, the lineaments played a role in drainage from the craton to the ocean. Overall, the apparent structures associated with these lineaments are a series of horst-graben sequences, creating highs and lows and affecting drainage patterns. The remnant domes are located on what were the topographic highs, with river drainage from the highlands located towards the northwest from the Canadian Shield following the faults along topographic lows shown in Figure 7C (Blakey, 2013).

As Dolly and Busch (1972) described, the areas of thicker lower member of the Wells Creek were topographic lows during the time of deposition of this fine-grained siliciclastic member, corresponding to deeper water conditions and allowing for preferential deposition of sediments. The areas of thinner lower member of the Wells Creek are the remnant domes, which were topographic highs with shallow water conditions that would have been above the fair-weather wave base. These thickness changes provide further evidence for the locations of these domes.

10.2 Reactivation of Lineaments and Influence on Deposition

Orientations of lineaments throughout the county occur in two directions that coincide with the regional structural fabric of the Appalachian Basin: northwest-southeast and northeast-southwest. These lineaments are interpreted to be faults that originated within the Precambrian basement and have been reactivated throughout time. There have been four major orogenies that spanned from the Early Ordovician to the Permian, with the convergent zone of all four orogenies oriented along the same northeast-southwest direction. Lineaments 1-9, located in the northwestern half of Morrow County, likely occurred in relation to Precambrian midcontinent rifting and reactivation from the four Paleozoic orogenies. Lineaments 10-14, located in the southeastern half of Morrow County can be linked to the development of the Rome Trough and likely have been reactivated during the four orogenies as well.

Determining timing of the reactivations of these faults during the Salinic, Acadian, and Alleghanian Orogenies cannot be completed here because the scope of this study focuses on Cambrian Ordovician strata; specifically, only strata associated with the Taconic Orogeny. The Taconic Orogeny spanned from Early to Late Ordovician time, with noticeable isopach variations in all formations except the Trenton Limestone (Figure 14D) and Utica/Point Pleasant Shale (Figure 15D). As noted, the lower shale package in the Wells Creek Formation infilled the erosional and structural topographic lows; (post Knox Unconformity) as sea level rose. Sea level continued to oscillate with the Tippecanoe Sequence depositing primarily carbonates and thin shale packages (Wells Creek and Black River Group; Figure 4). These carbonate and shale packages infilled erosional surfaces and the topographic lows within the Precambrian horst-graben sequences that were concurrently being compressed during the Taconic Orogeny.

During the deposition of the Late Ordovician units (Trenton Limestone, Point Pleasant/Utica Shale), there is little evidence of reactivation associated with the Taconic Orogeny and a regional cessation of deformation occurred in Morrow County during deposition of those two formations based upon thickness and structural trends. The Trenton Limestone and Utica/Point Pleasant were both deposited during the Late Ordovician, occurring during the second tectophase of the Taconic Orogeny. The Trenton Limestone is relatively thin (upwards of 29 ft (9 m)) and varies little throughout the county (Figure 14D). It is representative of a shallow, cool-water carbonate platform that extended across northwestern Ohio, followed by drowning of the platform during the onset of deposition of the Point Pleasant and Utica Shale (Ettensohn, 2010). The Utica Shale/Point Pleasant package also varies little throughout the county, from 168 to 189 ft (51 to 58 m) (Figure 15D).

The overlying Cincinnati Group and Queenston Shale vary in thickness by as much as 88 ft (27 m), and generally follow the regional thickening trend toward the south/southeast (Figures 16D and 17D). The inferred faults appear to have little influence on thickening or thinning of the formations during this time. This interval is dominated by mixed carbonate-siliciclastic sequences that were deposited in a shoaling-upward, storm-dominated environment (Wickstrom et al., 1992). The Queenston Shale is a delta lithofacies, associated with red shales deposited throughout the Appalachian Basin (Preston, 1985). These formations essentially form "blanket shales" and require lithofacies analysis to determine potential influence of structure during deposition. Bloxson (2017) did note lithofacies changes near Morrow County based on carbonate versus siliciclastic deposition, suggesting reactivation of faulting near the timing of deposition.

10.3 MORROW COUNTY FAULT SYSTEM

The deformation associated with the lineaments in Morrow County trending in both orientations represents an extensional system, creating two horst-graben sequences (Figures 18 and 19). The first sequence in the northern section with northwest-southeast trending lineaments, and the second northeast-southwest trending lineaments in the southern section of the county. The northwest-southeast trending lineaments first initiated in association with Keweenawan Midcontinent Rifting. It is likely the Fort Wayne Rift and/or the East Continent Rifting System (both extensions of the Keweenawan Midcontinent Rift) were the cause of the northwest-southeast lineaments in Morrow County. The Fort Wayne Rift trends northwest-southeast while the East Continent Rifting System trends approximately north-south. The Fort Wayne Rift is more probable due to rift orientation; however, the proximity and sparse knowledge of the two rifting stages suggest some deformation associated with the East Continent Rift seen in Morrow County.

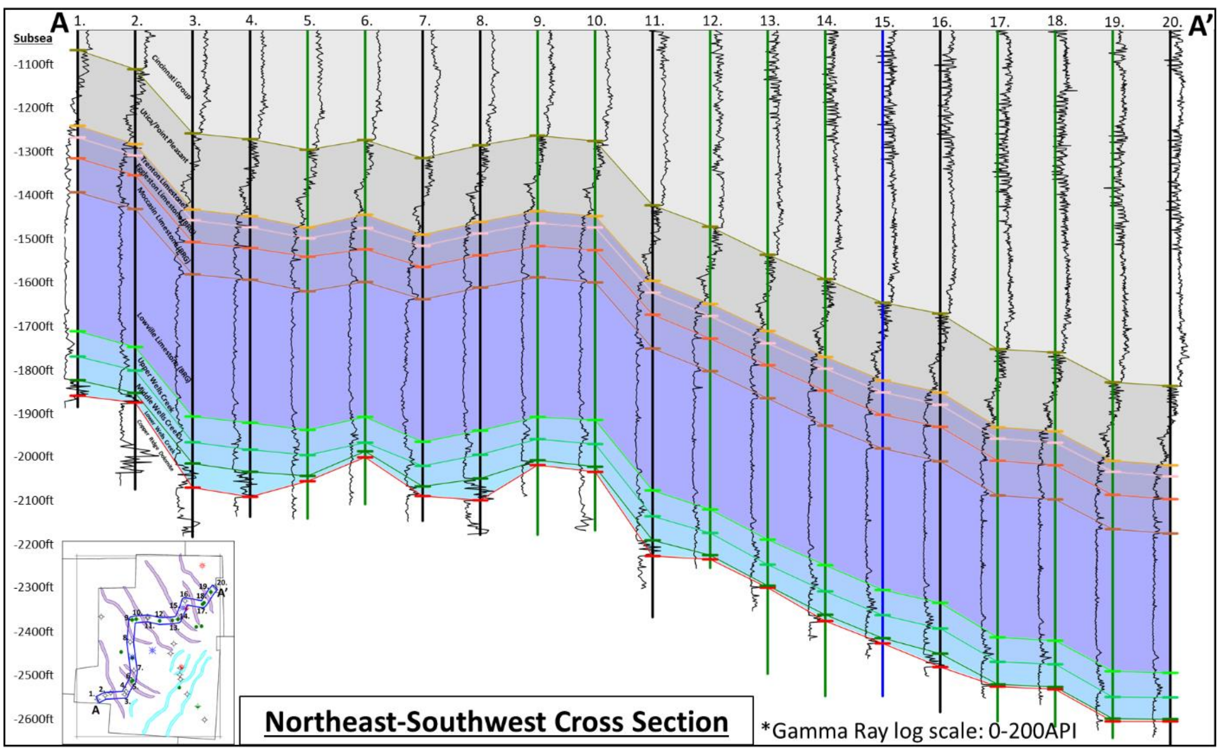

Figure 18. Northeast-southwest cross section intersecting lineaments 1-9, spanning over 20 wells.

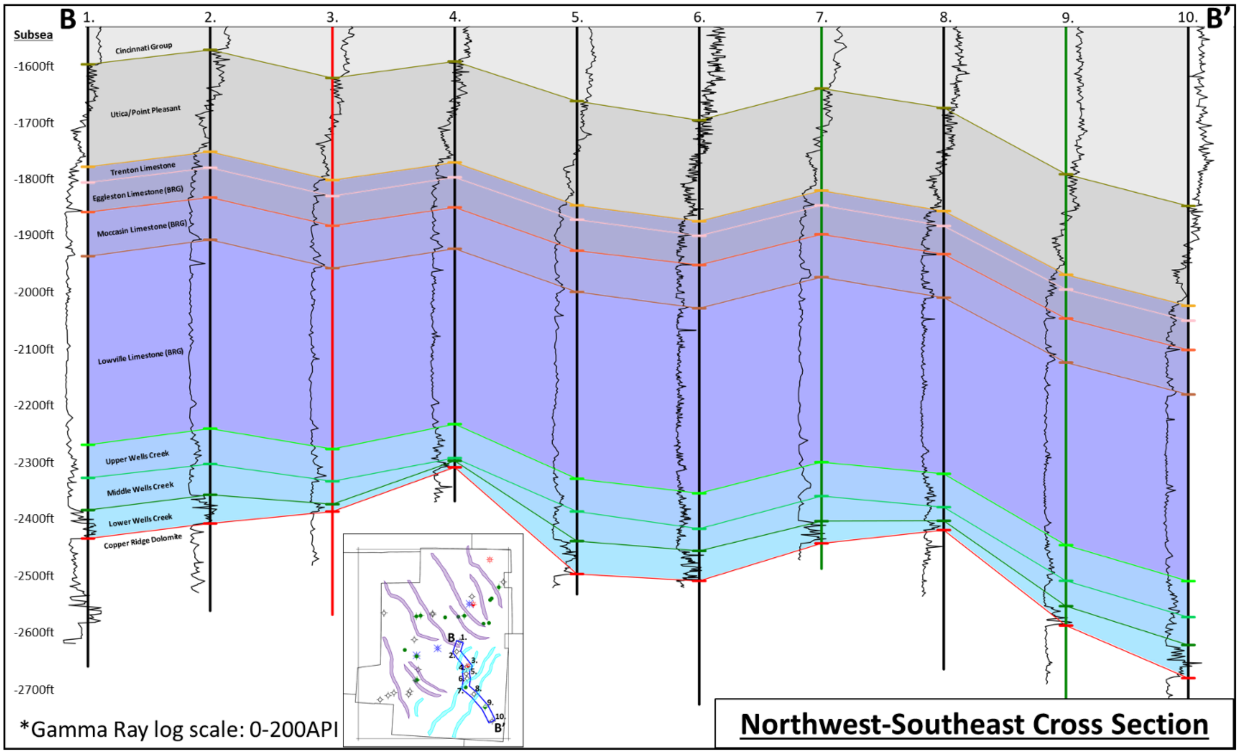

Figure 19. Northwest-southeast cross section intersecting lineaments 10-11 and 13-14, spanning over 10 wells.

Another likely source for the northwest-southeast lineaments in Morrow County is the Bowling Green Fault Zone. The Bowling Green Fault System has secondary faults that trend in the northwest-southeast direction, with the largest being the Outlet Fault Zone (Wickstrom et al., 1992). The Outlet Fault Zone that spans from Wood County to Wyandot County is approximately 35 mi (56 km) away from Morrow County, but it is on strike with the faults interpreted within the county. The northwest-southeast trending lineaments in Morrow County could be an extension of the Outlet Fault Zone and associated with the Bowling Green Fault Zone. There has been noted reactivation of the

Bowling Green Fault Zone during the four Appalachian Belt orogenies as detailed by Onasch and Kahle (1991) and Wickstrom et al. (1992).

The second set of lineaments, those that trend northeast-southwest in the southern half of Morrow County, likely occurred in conjunction with post-Grenville Iapetan Rifting, and resulted in the development of the Rome Trough (Figure 1 and 7-17C). The creation of the Rome Trough occurred during the Early to Middle Cambrian as Gondwana and Laurentia rifted (Iapetan Rifting) (Gao et al., 2020). Similar to the northwest-southeast lineaments in Morrow County, the northeast-southwest lineaments (faults) have been reactivated due to the Paleozoic orogenies. The Taconic, Salinic, Acadian and Alleghanian Orogenies have reactivated the faults found throughout the basin, affecting deposition and modern-day structure. Overall, these orogenies indicated that the basin (including Morrow County) has undergone numerous stages of compressional and extensional deformation.

10.4 STRUCTURAL INFLUENCE ON PRODUCTION

Initial production in Morrow County targeted remnant domes within the Copper Ridge Dolomite, which created “mini-reservoirs” that were capped by the siltstones and shales within the lower member of the Wells Creek (Dolly and Busch, 1972). Production data were taken from McClish and Roberts (1989) and Drilling Info (2020) and correlated to remnant domes and lineaments. Some of the production data from McClish and Roberts (1989) are from a producing field containing numerous wells; therefore, the data are combined into one well. It is impossible to decipher how much one well produced in that field, so in this study it was assumed that all wells in that field produced some amount, but only one well in the field is correlated with a production bubble indicator. All production data is listed in “total production.”

Overall, production primarily comes from remnant doming within the Copper Ridge Dolomite. Correlating the production data to the apparent remnant domes indicates that some domes produced relatively more oil, other domes produced more gas or water, and some domes did not produce (Figure 6). The lineaments appear to act as a migration pathway, rather than a potential trap, and reactivation of the lineaments appears to have caused secondary migration out of some remnant domes. For example, the upthrown block between lineaments 4 and 5 contains numerous dry holes, whereas to the southwest, a down-dropped block, the wells are prolific (Figure 23 and 24). This suggests that reactivation of lineaments 4 and 5 allowed for hydrocarbon migration up-dip.

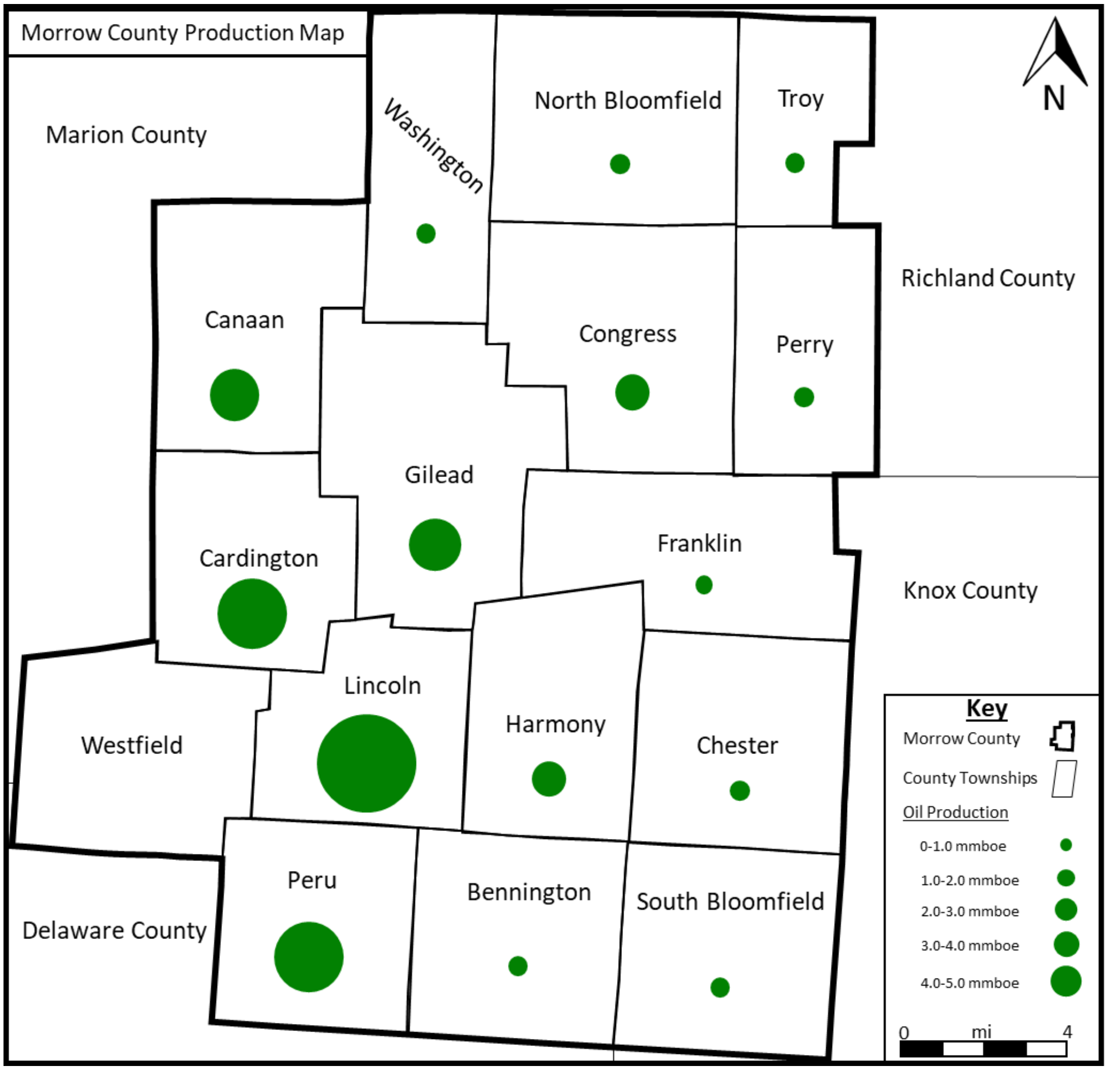

Figure 20. Production in Morrow County broken into Civil Townships. The cumulative production of the county is 30 million barrels of oil and 6.5 billion cubic feet of gas (Production data from: McClish and Roberts, 1989; DrillingInfo, 2020).

Lineament 1 bounds the eastern edge of the Westfield Township, which has little to no hydrocarbon production (Figures 20 and 21). The lineament acts as a migration pathway or barrier for hydrocarbon production; however, there is one well close to the lineament with an oil and gas show. Toward the southern end of the lineament in the Peru

Township, there are two wells which both produce significant amounts of oil (42,000 and 29,000 barrels) (Figures 20 and 21).

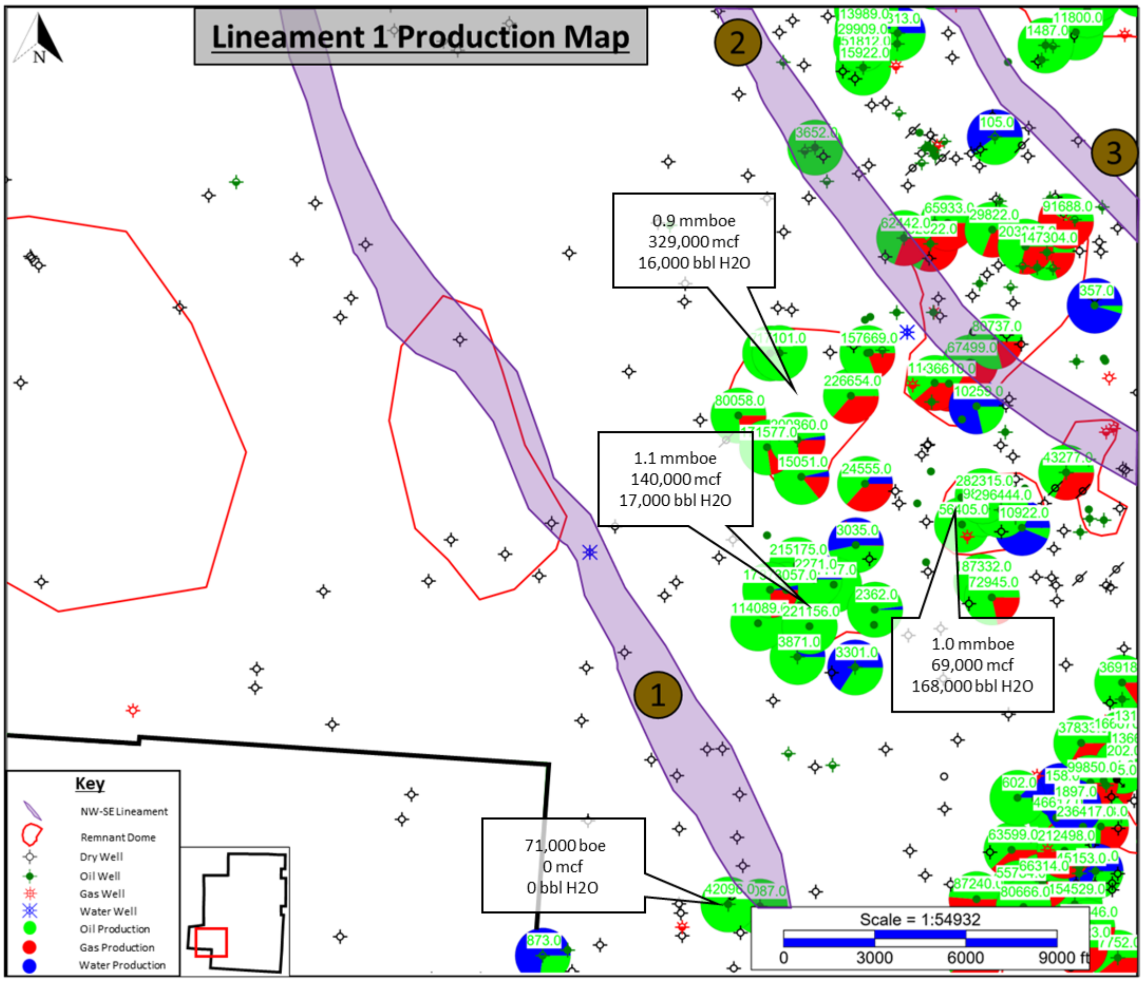

Figure 21. Production data in relation to lineament 1. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

Lineaments 2 and 3 have associated high remnant dome production. The southern end of lineament 2 has two producing domes: the most southernmost dome produced 237,310 barrels of oil with no recorded gas and water, and the northern dome produced

76,000 barrels of oil, 0 mcf of gas, and 156,000 barrels of water (Figure 22). In the northwest section of lineament 2, a well produced 43,000 barrels of oil and 20,000 mcf of gas within a dome. Toward the northern side of lineament 2, there is a dome split by the lineament. The southwestern side produced 404,000 barrels of oil, 193,000 mcf of gas, and 52,000 barrels of water, and the northeastern side has produced 539,000 barrels of oil and 308,000 mcf of gas. There is a linear string of oil producing wells on the northern edge of the lineament. This string of wells may be targeting a permeable joint/fault, as detailed by Shafer (1989), that may be a direct migration pathway for hydrocarbons. This string of wells produced 141,000 barrels of oil and 12,000 barrels of water. Similar to lineament 2, lineament 3 has many dry holes, but has only one large producing remnant dome. This dome is located on the northeastern side and toward the northern end of the lineament, and has produced 914,000 barrels of oil, 296,000 mcf of gas, and 155,000 barrels of water. Lineaments 2 and 3 are both likely migration pathways for hydrocarbons to migrate into and then be trapped in these remnant domes.

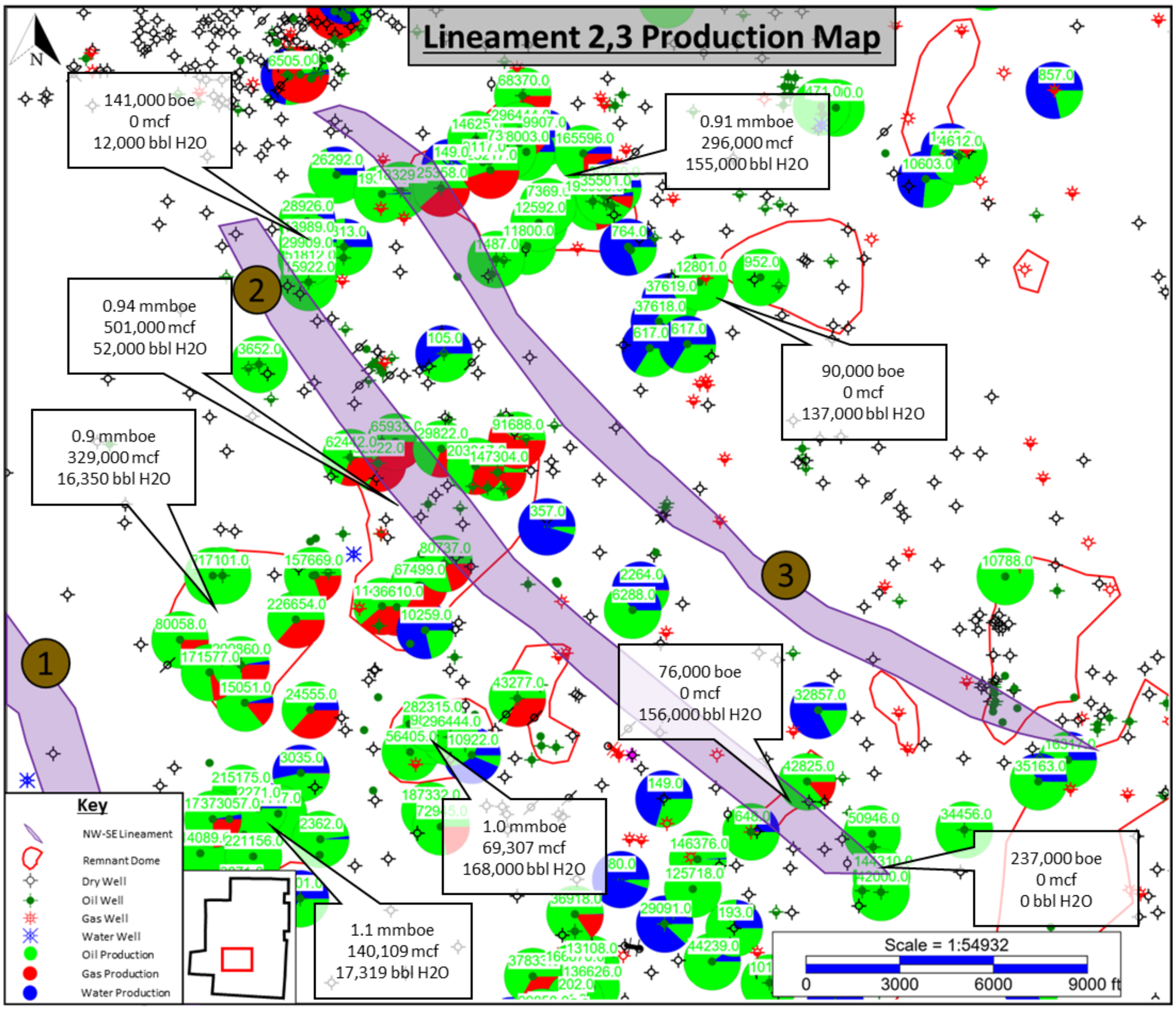

Figure 22. Production data in relation to lineaments 2 and 3. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

Lineament 4 bounds the southwestern side of the largest horst in Morrow County. There are numerous bounding productive and non-productive remnant domes on both sides of the lineament (Figure 23 and 24). Lineament 4 appears to have aided in migration of hydrocarbons to the domes along the southern side, whereas non-productive domes are located along the northeastern side of the lineament. There are significantly more dry wells along the lineament than there are productive wells. Lineament 5 is similar to lineament 4 in terms of playing a role in production; most all of the production is related to remnant doming, but yet again the lineament may play a role in hydrocarbon migration.

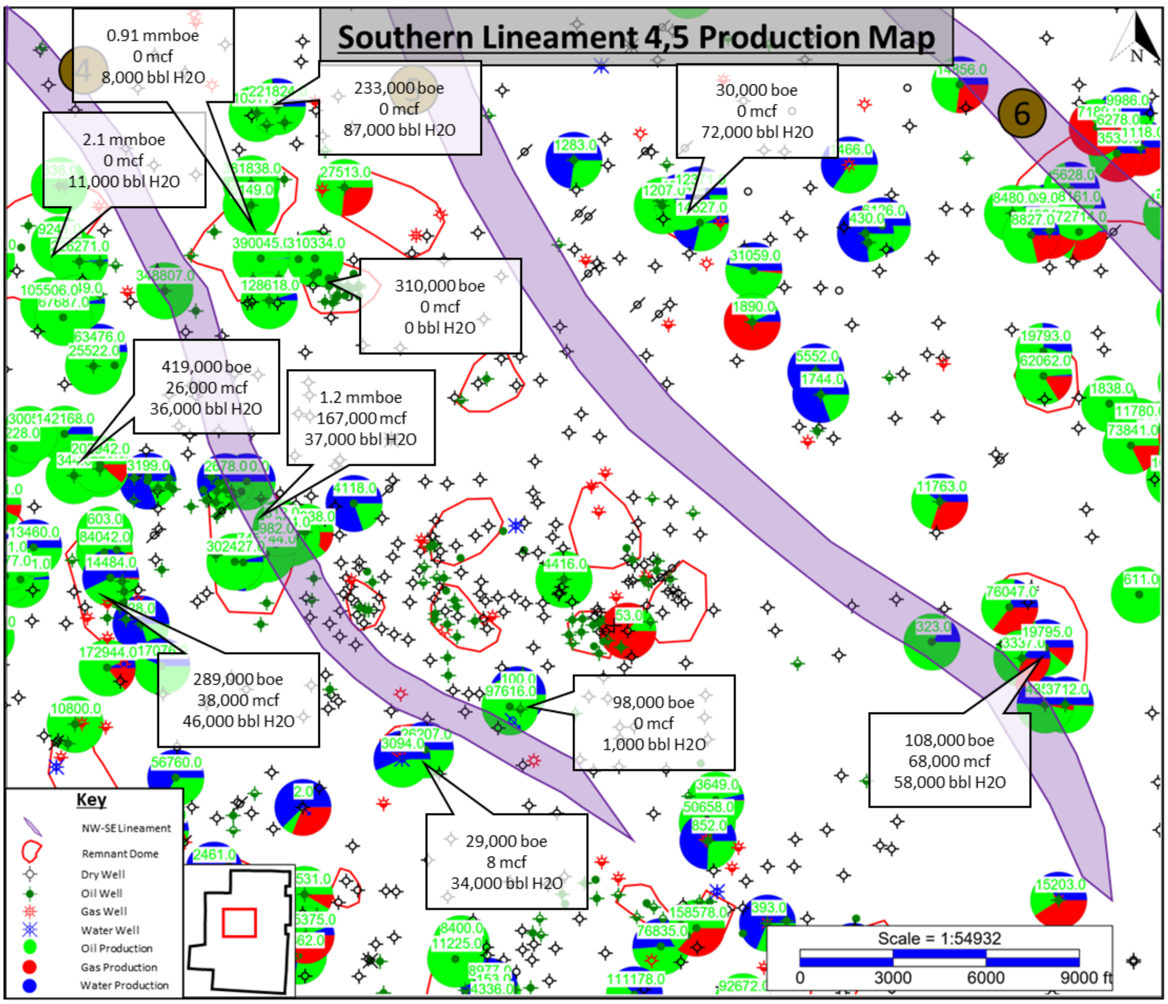

Figure 23.Production data in relation to the southern portion of lineaments 4 and 5. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

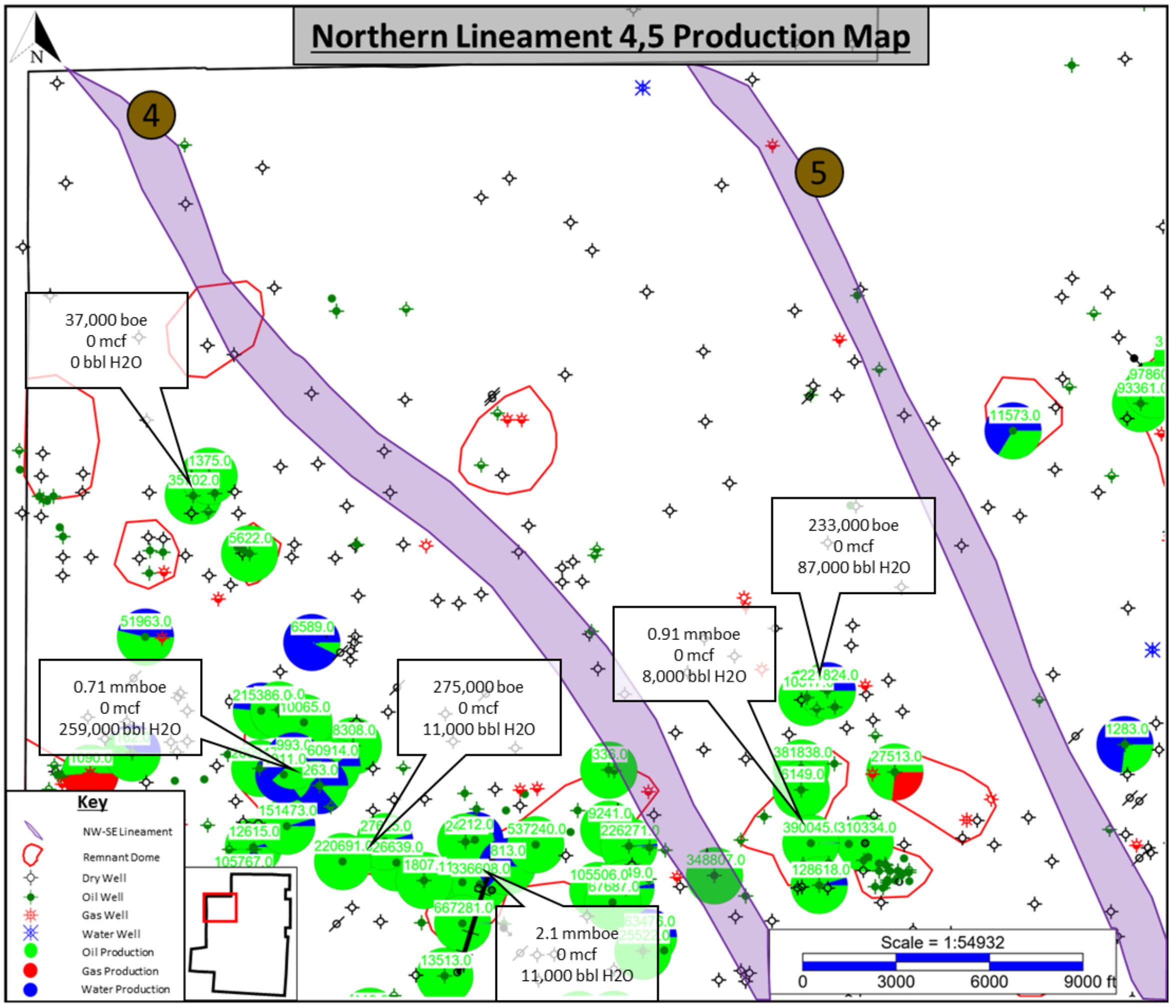

Figure 24. Production data in relation to the northern portion of lineaments 4 and 5. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

Lineament 6 is similar to previous lineaments, with most of the production coming from the remnant domes. However, lineament 6 appears to cut two different remnant domes in half. In the northern dome (Figure 25), the southern half of the dome produces nearly three times more than the northern half. In the southern dome (Figure 25), the southern half produces similar to the northern half. However, there are two wells centered on the lineament, one producing 158,000 barrels of oil and the other producing 52,000 barrels of oil.

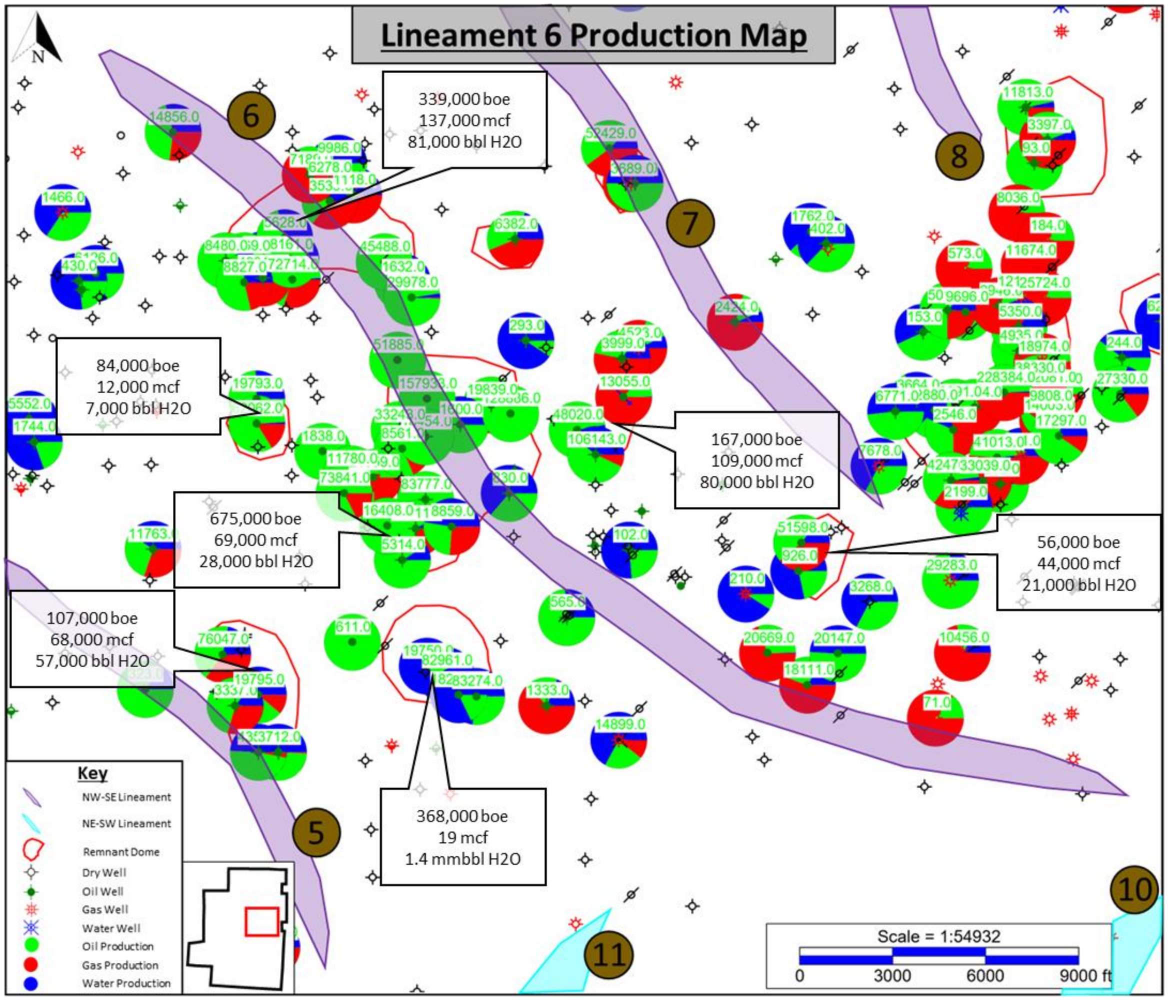

Figure 25. Production data in relation to lineament 6. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

Lineament 7 and 8 are very similar to the previous lineaments with dry holes and some producing wells along the lineament. Lineament 7 cuts through a remnant dome that produces approximately 58,000 barrels of oil, 66,000 mcf of gas, and 16,000 barrels of water. Production associated with lineament 7 tends to be more water-rich and lineament 8 tends to be more gas-rich (Figure 26 and 27). Both lineaments 7 and 8 produce minor amounts of oil and gas toward the northern end of the lineaments, compared to the southern end. The two remnant domes south of these two lineaments produced approximately 600,000 barrels of oil, 975,000 mcf of gas, and 79,000 barrels of water. Lineament 9 has more dry holes along the lineament trend than the other lineaments. There is a remnant dome north of lineament 9 that produced primarily gas and some oil. Just north of that dome is string of gas wells trending in a north-south direction (Figure 27).

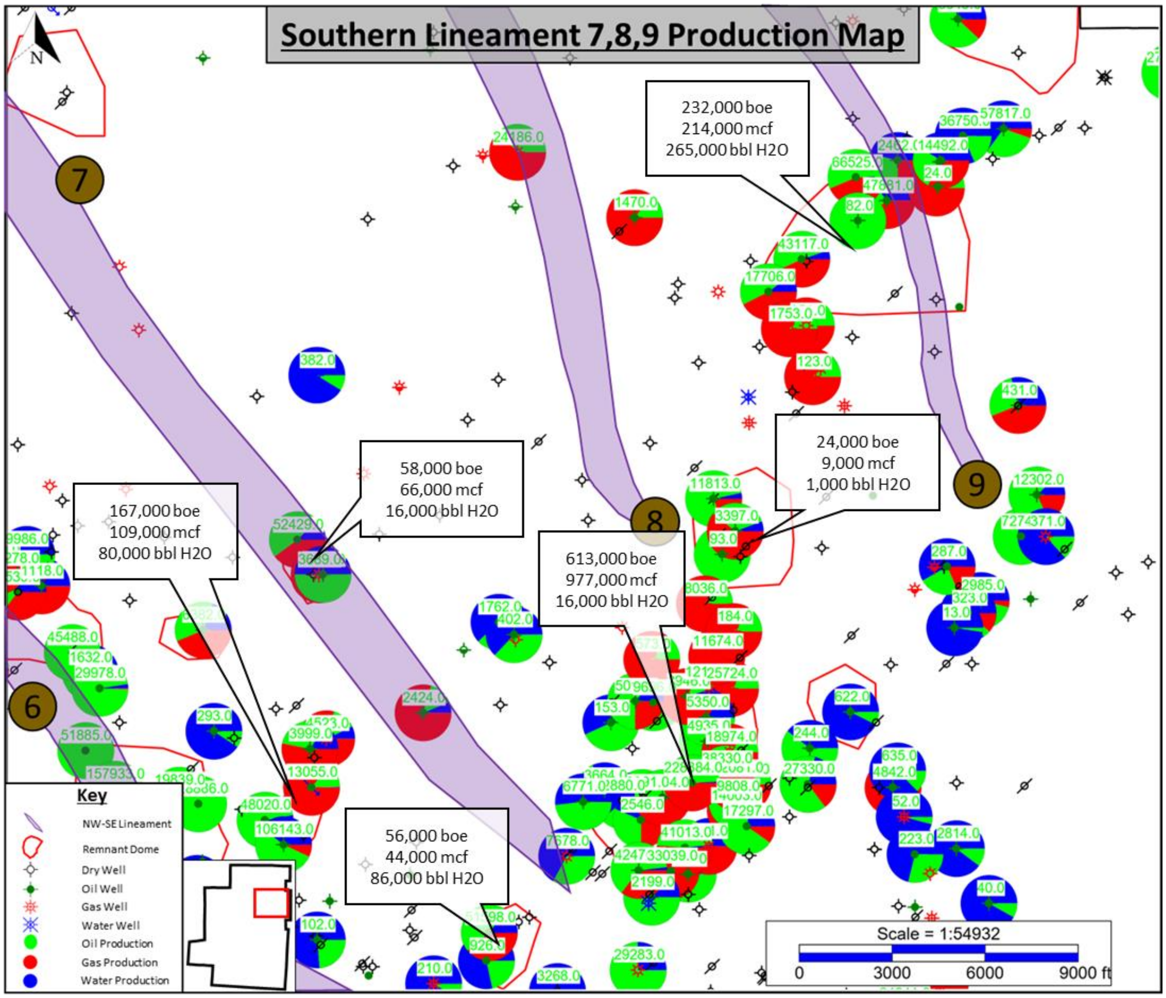

Figure 26. Production data in relation to the southern portion of lineaments 7, 8 and 9. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

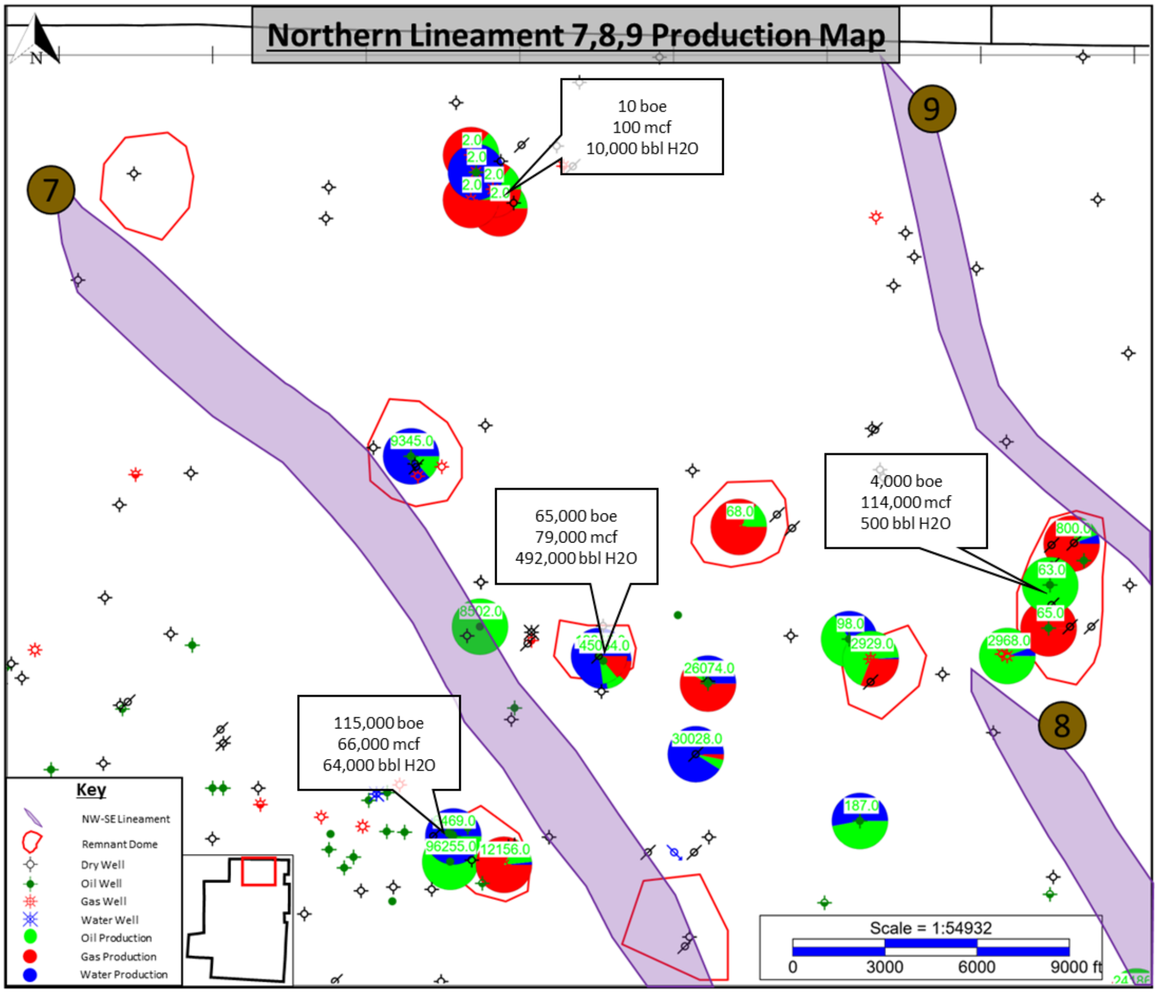

Figure 27. Production data in relation to the northern portion of lineaments 7, 8 and 9. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

Lineaments 10 and 11 (northeast-southwest) bound the other large horst found within Morrow County. The southern section of lineament 10 has two wells on the eastern side within a remnant dome that produced about 9,000 barrels of oil and water (Figure 28). On the western side of the same lineament, there is a well that produced approximately 23,000 barrels of oil and 66,000 barrels of water, not associated with a remnant dome. In the western mid-section of lineament 10, there is a dome that produced mostly water and an adjacent field to the east, which produced 188,000 barrels of oil and 42,000 barrels of water. The field that produced relatively more oil is located on the western edge of lineament 10 and doesn't appear to correlate with a remnant dome, so the lineament may be the reason for the production in this area. On the northern section of lineament 10, there is a cluster of wells that produced 15,000 barrels of oil and 31,000 barrels of water (Figure 29). Towards the southern end of lineament 11, the eastern bounding remnant dome produced mostly water, but on the western side of the lineament, the remnant dome predominantly produced oil (Figure 28). The rest of the western boundary of lineament 11 is ridden with dry holes, but on the eastern boundary there are a few oil producing domes, and some oil producing wells not correlated to domes.

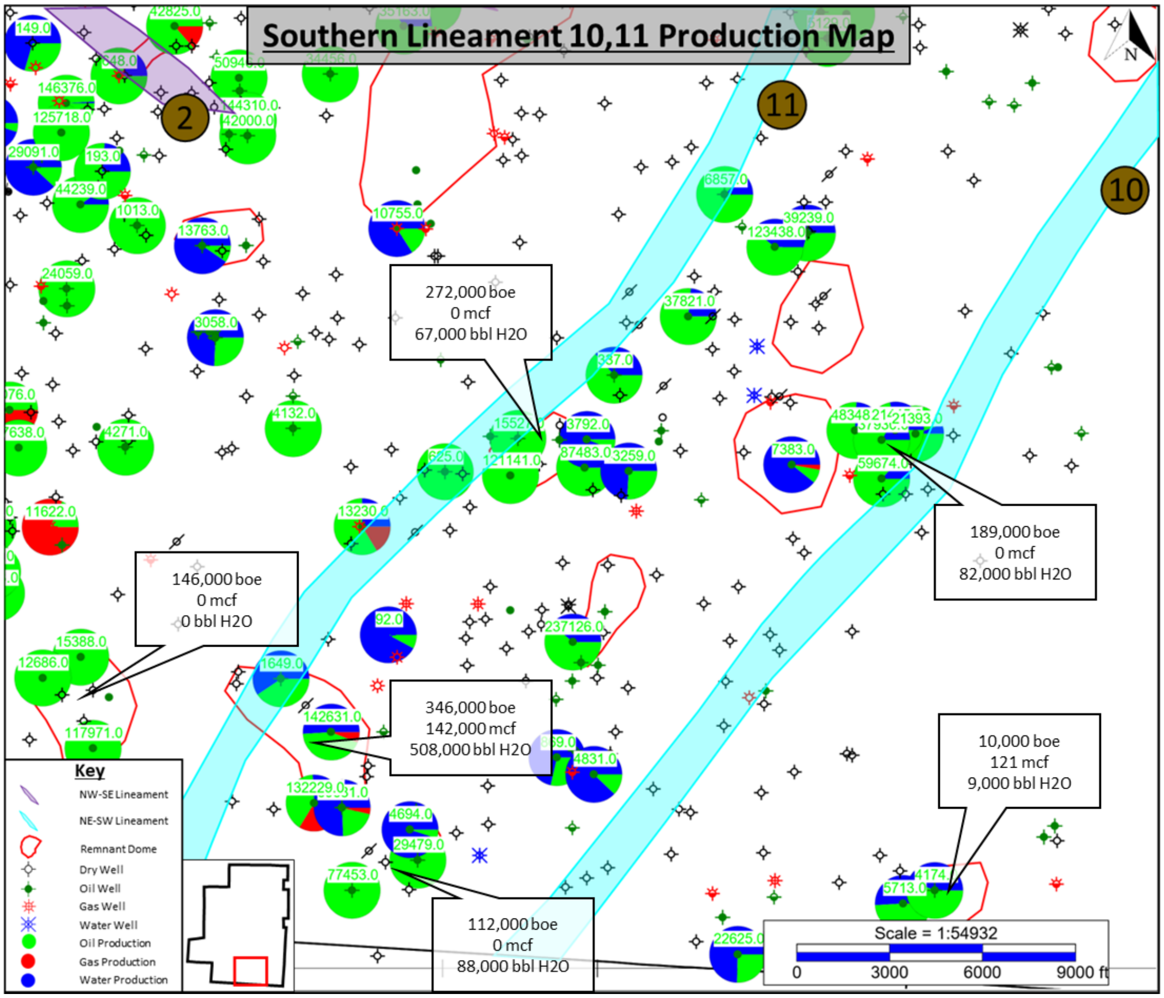

Figure 28. Production data in relation to the southern portion of lineaments 10 and 11. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

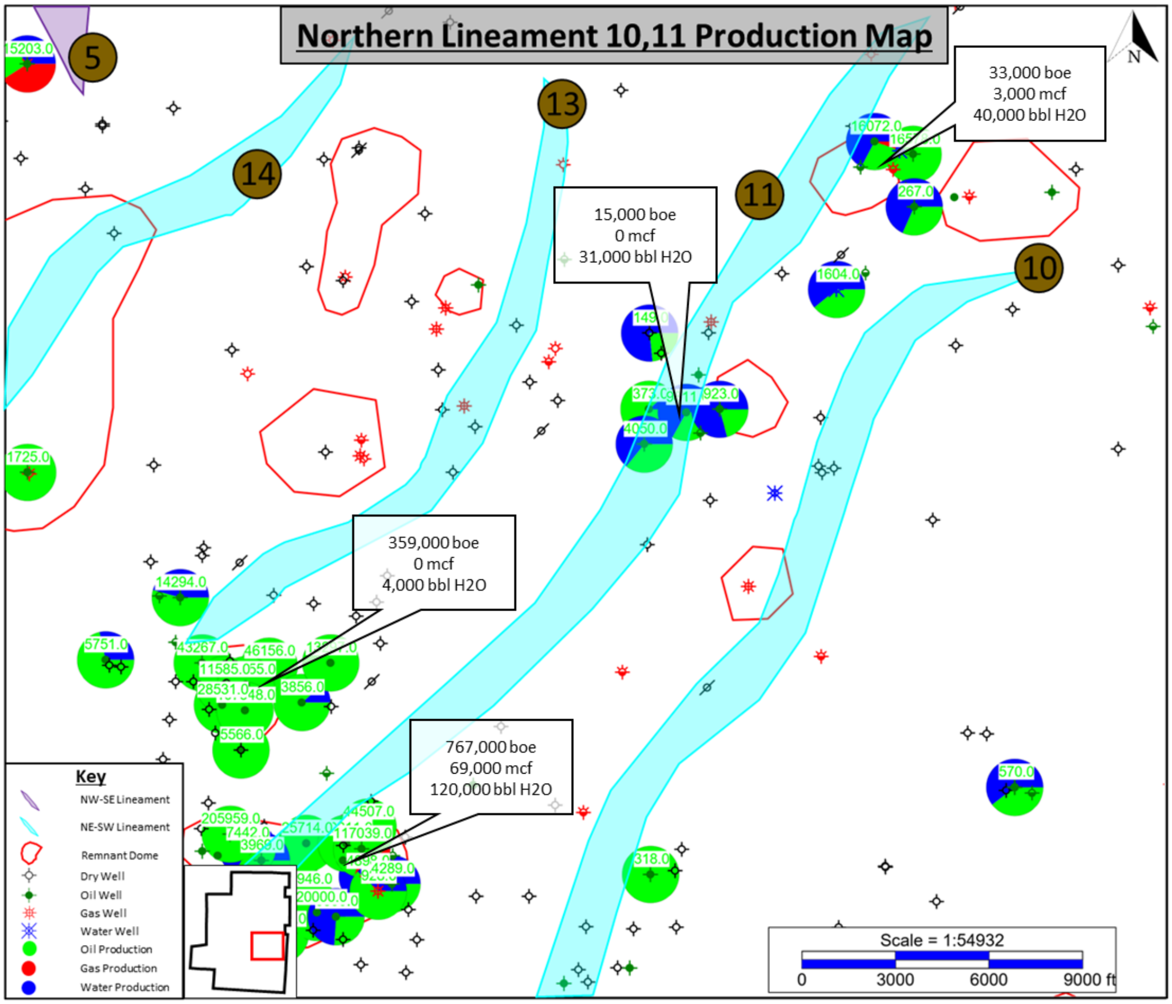

Figure 29. Production data in relation to the northern portion of lineaments 10 and 11. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

Lineament 12 is the most intriguing lineament in the whole county, as there are atypically large remnant domes on the eastern side of the lineament (Figure 30). The lower dome has produced 998,000 barrels of oil, 564,000 mcf of gas, and 0 barrels of water. The northern dome produced 1,732,000 barrels of oil, 562,000 mcf of gas, and

290,000 barrels of water. The bounding of lineament 12 with the two remnant domes indicates proof that the lineament is a migration pathway for hydrocarbons. Lineaments 13 and 14 differ from all other lineaments in terms of production. The remnant dome south of lineament 13 is the only major producing area (Figure 31). This dome has produced 329,000 barrels of oil, 250 mcf of gas, and 4,000 barrels of water. Lineament 13 does not transect a dome but could still be a migration pathway for hydrocarbons. The northern portion of lineament 13 is associated with dry holes and as is lineament 14.

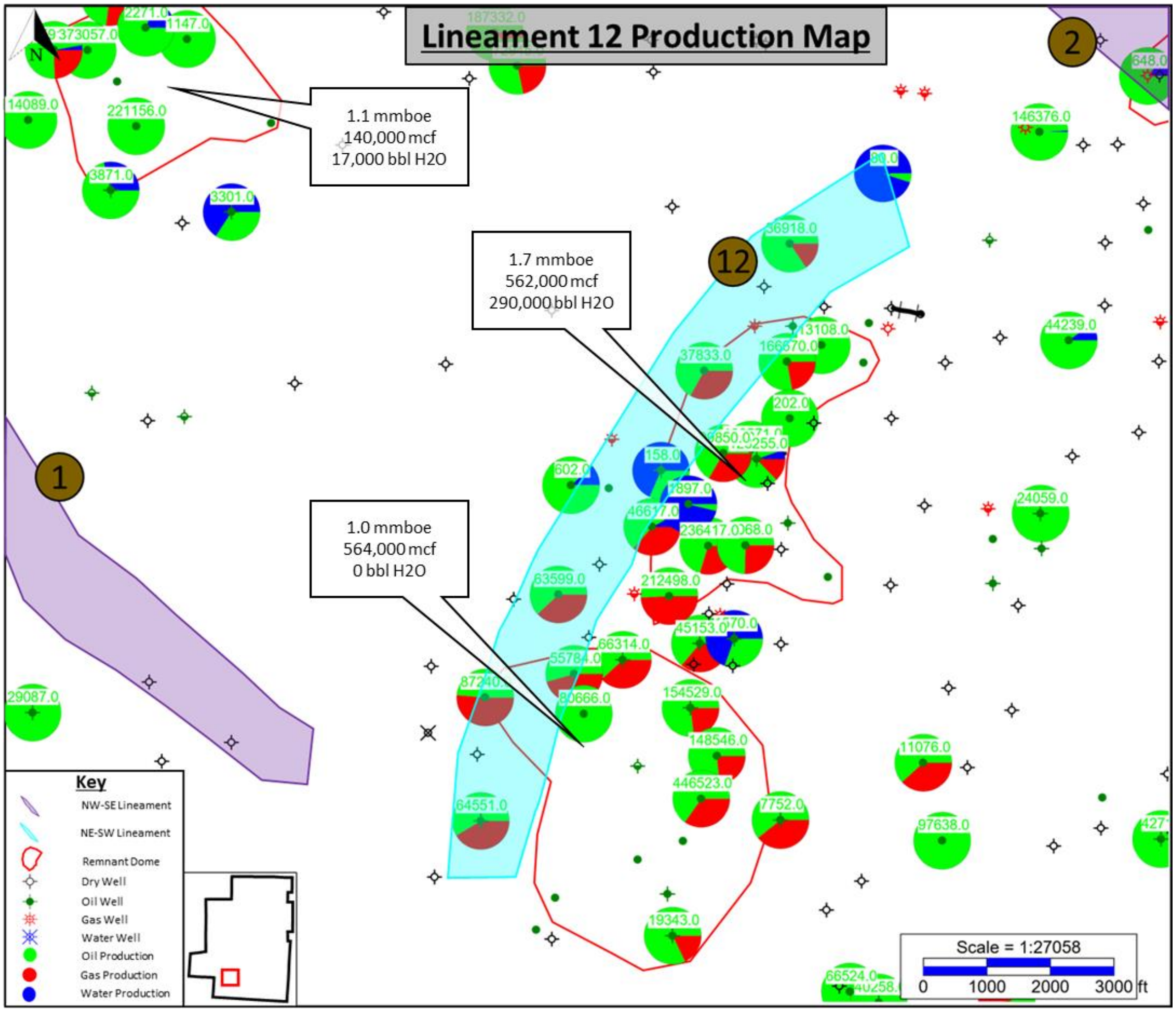

Figure 30. Production data in relation to lineament 12. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

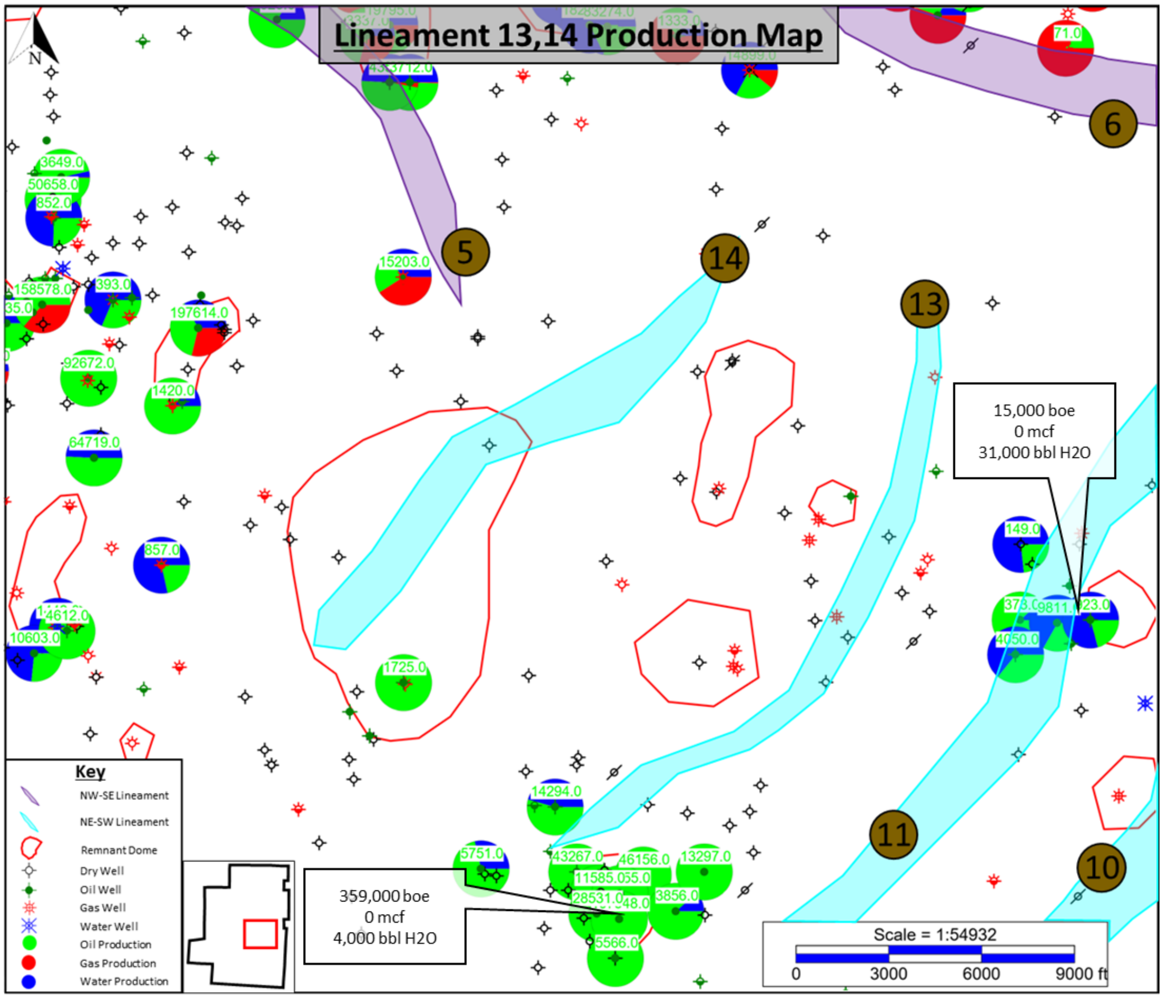

Figure 31. Production data in relation to lineaments 13 and 14. Total production for one well split into oil (green), gas (red) and water (blue) pie charts. Total oil production for one well in green text. Total oil, water, and gas production in bubbles.

11 LOOKING FORWARD

The scope of this study was limited to log and production data only, but access to seismic data, preferably 3D seismic, would verify the lineaments interpreted in this study. Seismic data would confirm or deny the horst-graben sequences hypothesis, and would also help identify the movement of the faults in the area, as well as the remnant domes. Core studies would allow for a better interpretation of lithofacies changes and gain an understanding of the origin and location of the source rock fueling production within Morrow County.

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13 APPENDIX

13.1 WELL DATA

All data are in feet, relative to measure depth, and sorted by UWI number. Well data can be found in an attached excel document, on https://scholarworks.sfasu.edu/etds/.

13.2 PRODUCTION DATA

All oil and water production data are in barrels and gas production in thousand cubic feet, and sorted by UWI number. Production data can be found in an attached excel document, on https://scholarworks.sfasu.edu/etds/.

14 VITA

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